Ministry of Transportation
Ontario

REPORT MI-140

REVIEW OF MINISTRY END RESULT SPECIFICATIONS

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Review of Ministry End Result Specifications

Author: James L. Burati, Jr. and Serji N. Amirkhanian

Abstract:

In 1989 the Ontario Ministry of Transportation hired Dr. J. Burati to carry out a review of several end result specifications which were in use by the Ministry or under development. Dr. Burati was asked to review these specifications and guidelines, point out any statistical flaws, and to comment on the fairness of the specifications to the Ministry and the industry. The review was to include statistical analysis, development of operating curves and assessment of buyers and sellers risks.

The details of the review are given in this report which is divided into sections covering Soils and Aggregates, Concrete Materials and Bituminous Materials. The authors recommend that the Ministry consider changes to some of the specifications. Typical examples are:

1) Use of "standard deviation" and "per cent within limits" rather than "range requirements" or "mean only" in some specifications.
2) Use of continuous payment schedules rather than stepped schedules in some areas.
3) Increased randomness in sampling procedures.

The recommendations will be considered by our Quality Assurance Systems Committee and will be adopted by the Ministry except in areas where we have strong reasons for retaining the present procedures.

Résumé:

En 1989, le ministère des Transports de l'Ontario a retenu les services de M. J. Burati pour revoir plusieurs spécifications régissant les résultats finals qu'utilise actuellement le ministère ou qui sont en cours d'élaboration. On a demandé à M. Burati d'étudier ces spécifications et directives, de relever les erreurs statistiques et de présenter ses observations relativement à l'équité des spécifications au ministère et à l'industrie. Cette étude devait comprendre une analyse statistique, élaborer de nouvelles courbes opérationnelles et évaluer les risques que pourraient courir les acheteurs et les vendeurs.

Les résultats de cette étude figurent dans le présent rapport qui est divisé en sections portant sur les sols et les agrégats, le béton et les matériaux bitumineux. Les auteurs recommandent au ministère de modifier certaines des spécifications, notamment de la façon suivante :

1) En utilisant un écart type et des limites exprimées en pourcentage plutôt que des plages de résultats et en n'utilisant plus exclusivement les moyennes pour certaines spécifications.
2) En utilisant des calendriers continus de paiement plutôt que des horaires graduels dans certains secteurs.
3) En élargissant le caractère aléatoire des procédures d'échantillonnage.

Les recommandations seront prises en considération par notre comité des systèmes d'assurance de la qualité et seront adoptées par le ministère, sauf dans les secteurs où l'on estime qu'il serait préférable de conserver les procédures utilisées à l'heure actuelle.

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Serji N. Amirkhanian

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CHAPTER 1 - SUMMARY

GENERAL

This report summarizes a review of certain Ontario Ministry of Transportation (the Ministry) end result specifications and some of their supporting documents that were provided by the Ministry. The review was conducted with regards to the statistical aspects of the specifications, and did not attempt to judge or to validate the technical requirements, such as tolerance limits, etc., of the specifications. In the statistical review, factors such as statistical flaws, levels of risk to the owner and seller, and the operating characteristics of the acceptance procedures were considered.

OPERATING CHARACTERISTICS CURVES

Where appropriate, Operating Characteristics (OC) Curves were developed. The OC curves presented in this report were generated by computer simulation assuming that the underlying distribution of the material in question was normal. No data were available to verify this assumption. However, this is a very common assumption that has been found to be appropriate for many different construction materials.

The OC curves were developed for various process variabilities, as represented by selected standard deviations, σ. The values of σ selected for developing OC curves were obtained, where possible, from information provided by the Ministry. An additional source of variability information that was used to augment the values from the Ministry, or as the sole source of information when no data were available from the Ministry, was a series of articles appearing in Public Roads from February-December, 1969 (1). While this source appears to be somewhat old, a draft Federal Highway Administration Technical Advisory (not yet issued) on Specification Conformity Analysis still refers to these articles as "A good source of information on materials variations ..."

PERFORMANCE OF THE ACCEPTANCE PROCEDURES

In general, the acceptance procedures performed as intended by the Ministry. That is, the OC curves indicated that the contractor should be encouraged by the price adjustments to meet the specification requirements.

Acceptance plans are often evaluated by comparing the buyer's risks (β) and the seller's risks (α). This is appropriate for accept-or-reject decisions. When price adjustments are employed, the decision is more often 'how much' should be paid rather than whether the material should be accepted or rejected. In this case, the risk to the owner is that the payment will be greater than called for in the payment schedule, while the risk to the contractor is that a lower payment than called for in the payment schedule will be received. These 'risks' can be assessed by comparing the expected payment values from the OC curves with the payment levels that are called for in the acceptance procedures.

In general, for the OC curves presented in this report, the expected payment values correspond to the payments called for in the acceptance procedures. However, as pointed out in the appropriate discussion sections, where only the sample mean is used for acceptance decisions there is no method for controlling the variability of the material. Also discussed in the report is the potential bias toward a low expected payment for populations with expected payments near 100%. This is due to the upper limit of full (i.e., 100%) payment which is imposed. This bias is a risk to contractors which is inherent in acceptance procedures which do not allow bonuses or some form of credit for lots which exceed the requirements for full payment. Smart contractors can adjust to this bias by modifying their process targets and/or adjusting their bid prices.

It is recommended that the Ministry consider adopting the Percent Within Limits (PWL) method for evaluating the acceptability of more materials. This method incorporates the control of both mean and variability into the calculation of a single value (i.e., the PWL) which can be used for acceptance and payment determination decisions. The PWL approach is currently

used in some of the Ministry acceptance procedures evaluated in this report. Its use for evaluating other materials would simplify the acceptance procedures which currently use limits for both sample mean and sample Range. The PWL approach, which considers both mean and variability, would be a significant improvement for the procedures which currently base acceptance decisions on only the sample mean.

Even when using the PWL approach, there are risks associated with the acceptance decision. The risk of making an incorrect acceptance or payment determination decision reduces as the sample size increases. As shown in the discussion on compaction of earth and granular materials, the risks can be relatively high for the small sample sizes, such as n = 4, which are typically used in highway construction.

REPORT ORGANIZATION

The discussions in the report are divided into major materials areas, including **Soils & Aggregates**, **Concrete Materials**, and **Bituminous Materials**. Each of these sections begins with a general discussion of the statistical aspects of the related acceptance procedures, including sampling and testing aspects. Where appropriate, the sections conclude with the presentation and discussion of OC curves which represent the acceptance procedures and the risks associated with them.

CHAPTER 2 - SOILS AND AGGREGATES

INTRODUCTION

The information reviewed in the Soils & Aggregates area was from the manual entitled Testing of Soils & Aggregates dated December 1982 and authored by the Engineering Materials Office. While the total document was reviewed, at the request of the Ministry, the following specific pages were reviewed with respect to their statistical bases:

Compaction of Earth and Granulars	
pp. 2-8 to 2-19	One Point Proctor
pp. 2-37 to 2-46	Specification
pp. 2-47 to 2-55	Procedures
Granular Gradation & % Crushed	
pp. 3-1 to 3-10	Sampling Procedures
pp. 3-11 to 3-16	Testing Procedures
pp. 3-26 to 3-36	Specification
pp. 3-38 to 3-41	Forms

In addition, the following supporting documents that were provided by the Ministry were reviewed as sources of variability information:

"An Evaluation of Compaction Control of Granular Base and Subbase Aggregates," Report EM-39, Engineering Materials Office, Ontario Ministry of Transportation and Communications, March, 1981.

"Statistical Evaluation of Gradation Test Results for Base and Subbase Aggregates - 1980 Construction Season," Report EM-53, Engineering Materials Office, Ontario Ministry of Transportation and Communications, August, 1981.

GENERAL COMMENTS

The following comments relate to the review of the above materials relating to soils and aggregates. The comments are presented individually, and, where appropriate, suggestions or recommendations are presented.

Compaction of Granular and Earth Materials

1. The tables of random numbers (Tables 1 and 2) presented on pages 2-5 and 2-6 are fairly limited. Tables of this size could possibly introduce some sampling bias. Also, the fact that the table is divided into groups of two random numbers, the first representing the station and the second representing the offset, will lead to the same combinations of station and offset if the tables are used more than once.

It should be possible to increase the number of random numbers in the tables by adding additional columns and by decreasing the top and bottom margins. This would allow additional random numbers while still requiring only a single sheet of paper printed front and back.

Consideration should also be given to not separating the numbers into groups of two. By having a continuous listing of numbers, more random numbers would be possible and it would be less likely that the same combinations of station and offset would be repeated. The current format was obviously adopted for ease of use in the field. This convenience of use must be weighed against the possible bias that may be introduced. By having more random numbers and not subdividing them into groups of two (the instructions would be to take two consecutive numbers with the first for station and the second for offset) the tables should have less chance of introducing bias into the sampling process.

2. On page 2-39, two methods, Method A and Method B, are presented for determining the acceptability of compaction. It is stated that, unless otherwise specified in the contract, Method A will be used. Method A states that one of five procedures may be used to make the density determination. Since these methods are likely to have different variabilities, if the acceptance limit was developed based on one of the methods, and another of the methods is used for the acceptance decision, the acceptance limit may not be appropriate.

By correspondence, Mr. Malcolm McLean has indicated that the Ministry uses Method B. This is definitely preferable to Method

A. Method A appears to be based on single sampling and does not consider material variability. If this is the case, its use, even by small local municipalities should be reconsidered in favor of a method which considers variability and stipulates a specific test method.

3. Method B on page 2-39 is based on the Percentage Within Limits (PWL) concept which considers both mean and variability in the determination of PWL. The procedure is based on the Range method. In his letter, Mr. McLean indicated that the Range method was chosen because it is easier to understand, calculations are easier, and calculation errors are less likely. With the widespread use of calculators which have the capability of calculating means and standard deviations, it is doubtful that the Range method should be preferred over the standard deviation method for calculating PWL. The standard deviation method for calculating PWL provides a better estimate of PWL for a given sample size than is provided by using the Range. Very little change in the specification would be required to substitute the standard deviation for the range. Tables of quality indexes for the standard deviation method are widely available and are being used by a number of highway agencies.

4. On page 2-41, the acceptance decision is based on having an estimated 99 PWL and a Range $\leq$ 15%. It is probably more common to base acceptance only on the PWL value. The Range requirement may have been added to ensure a degree of uniformity in the material. In his letter, Mr. McLean states that few, if any, lots have both PWL $\geq$ 99 and R $\geq$ 15. If this is the case, then the Range limit may not be necessary. For lots with means near the acceptance limit, the PWL determination will ensure that the Range is not too large. The Ministry may wish to collect some data to determine how often lots with PWL $\geq$ 99 have required rework because the Range exceeded 15%. If all lots with Ranges in excess of 15% also have PWL $\leq$ 99, then the Range requirement could be eliminated in future issues of the specification.

The wording on page 2-41 which states that "Where Qi has a positive value equal to or greater than 0.66, then 99 percent of the lot will have compaction above the specified limits" is not technically correct. If Qi ≥ 0.66, then the estimated PWL is ≥ 99. It is never possible to know the true PWL since it is not possible to test all of the material in the lot.

The value of Qi used to represent 99 PWL is given as 0.66 on page 2-41. This value is in accordance with the tables in AASHTO R9-84. However, a paper published by Weed in Transportation Research Record 1056 (2) presents a table for estimating PWL by the range method (variability unknown) which lists the PWL value as 99.1 (it actually indicates 0.9% defective) for a Qi of 0.65 and a PWL of 100 (0% defective) for a Qi of 0.66. The Ministry may wish to review this paper and consider revising the acceptance decision to a Qi of 0.65.

5. Regarding the random sampling locations (page 2-53) for the control strip, stratified random sampling should be considered as an alternative. While the control strip is a relatively small area, with pure random sampling it is still possible that all three of the tests could be taken from half or less of the length of the control strip. When the total of ten sample locations are taken, then stratified sampling is probably not necessary. However, consideration should be given to using stratified sampling when three values are obtained from the control strip.

Sieve Analysis and Percent Crushed Testing

1. On page 3-1, four sampling locations are provided for obtaining aggregate samples. It is likely that the four locations will have different sampling variabilities. This fact should be considered when establishing the acceptance limits. If the limits were established based on sampling from the stockpile, and then the samples are obtained from the roadway, then the limits may not be appropriate. When developing acceptance procedures, it is important that the acceptance limits be developed based upon the same procedures that will be used during the acceptance testing. To limit the variability of the sampling and testing process, the

sampling location should be part of the acceptance plan. The Ministry should consider collecting some data to determine whether similar results are obtained from the four different sampling locations. If all four sampling locations were used to collect the data that were used to establish the acceptance criteria, then the acceptance requirements are probably based on some sort of "average" sampling variability. This should be sufficient if the difference among the sampling variabilities of the four locations is not a great. However, if the acceptance limits were developed primarily from a single sampling location, then consideration should be given to requiring this sampling location in the specifications unless there are data available to indicate otherwise.

2. The same comments regarding random number tables that were made in **item 1** under **Compaction of Granular and Earth Materials** apply to the discussion of random number tables presented on page 3-3. Instead of stabbing a pen or pencil to find a starting location, the procedure could use dice or numbers could be drawn from a hat to determine the column and row in which to begin in the random number table. It may also not be necessary to subdivide the table into groups of four random numbers. A continuous table would allow additional numbers to be included in the same amount of space.

3. Regarding aggregate gradation requirements, with adjustment points for each sieve and for percent crushed, and with up to eight sieves, the potential price adjustments could be quite severe. There is also the potential of correlation problems with using all of the sieves for acceptance purposes. If there is a correlation between percent passing from one sieve to the next, then having adjustment points for all sieves could penalize the contractor more than once for the same deficiency. Mr. McLean's letter indicates that very few lots are "really bad" each year (5 or 6 out of about 1000).

Regarding the adjustment points, Mr. McLean indicates in his letter that controlling the 75 μm and 4.75 mm sieves was considered critical to avoiding serious pavement problems. The adjustment points for these sieves were established so that the maximum reduction in payment, 25%, coincided with the maximum deviation from the specification limit that would be allowed before the material was required to be removed. He also indicates that the intermediate sieves were not felt to be as significant and that the adjustment factor was assigned as 0.1.

Since the 75 μm and 4.75 mm sieves are considered to be crucial, it may be an option to require acceptance and payment decisions for only these two sieves, and to control the other sieves as part of the requirements for the contractor's or supplier's quality control plan. This would allow the intermediate sieves to be monitored for control purposes while avoiding potential problems with correlation among the percent passing of the various sieves. However, this may not be a problem since the data supplied by Mr. McLean regarding price adjustments over the last seven years do not indicate that significant price reductions have occurred very often.

4. Rather than using both mean and range for acceptance decisions, consideration should be given to switching to the use of PWL for acceptance decisions. The PWL combines both the mean and range (or, preferably, σ) into a single number for acceptance decisions. The PWL concept is already employed in the **Compaction of Granular and Earth Materials** acceptance procedures.

OC CURVES

OC curves were developed for **Compaction of Granular and Earth Materials** and for **Sieve Analysis**. No data were available regarding standard deviation values to represent the process for Percent Crushed Testing, so no OC curves were developed at this time. If the Ministry has data available for this test, then OC curves could be developed at a later time.

Compaction of Granular and Earth Materials

Computer simulation was used to develop separate OC curves for percent compaction for granular and earth materials. The curves were based on the assumption that the process could be represented by a normal distribution. Ministry Report EM-39 and the Public Roads (1) articles were used to establish a range of standard deviation values to represent the process variability for each of the OC curves.

The acceptance for compaction of granular and earth materials is based on the PWL approach using the mean and range from a sample of size n = 4. The simulation program generated 1000 samples of size n = 4, and then determined the PWL value for each sample. The OC curves plot, for various standard deviations, the probability that rework of the material will **NOT** be required versus the population mean of the material. The OC curves were developed in this manner because the population mean and standard deviation are easier to understand and to directly control than is the PWL of the population.

The OC curve for percent compaction for earth materials is presented in Figure 1, while the OC curve for percent compaction for granular materials is presented in Figure 2. The earth material compaction acceptance requirement is that an estimated 99 percent of the material must exceed 90 percent compaction. The granular material compaction acceptance requirement is that an estimated 99 percent of the material must exceed 95 percent compaction. Since the same standard deviations were used in both OC curves, and since the only difference in the acceptance requirements is in the acceptance limit (90% versus 95%), the two sets of OC curves have the same shape. If the mean and standard deviation of the compaction process are known from historical data, then the Ministry or a contractor can use these curves to estimate the likelihood that the acceptance requirements can be met without requiring reworking.

The data in Report EM-39 indicate σ values in the 1.5 percent to 3.5 percent range. With a σ of 1.5 percent, essentially no rework will be required as long as the population mean compaction

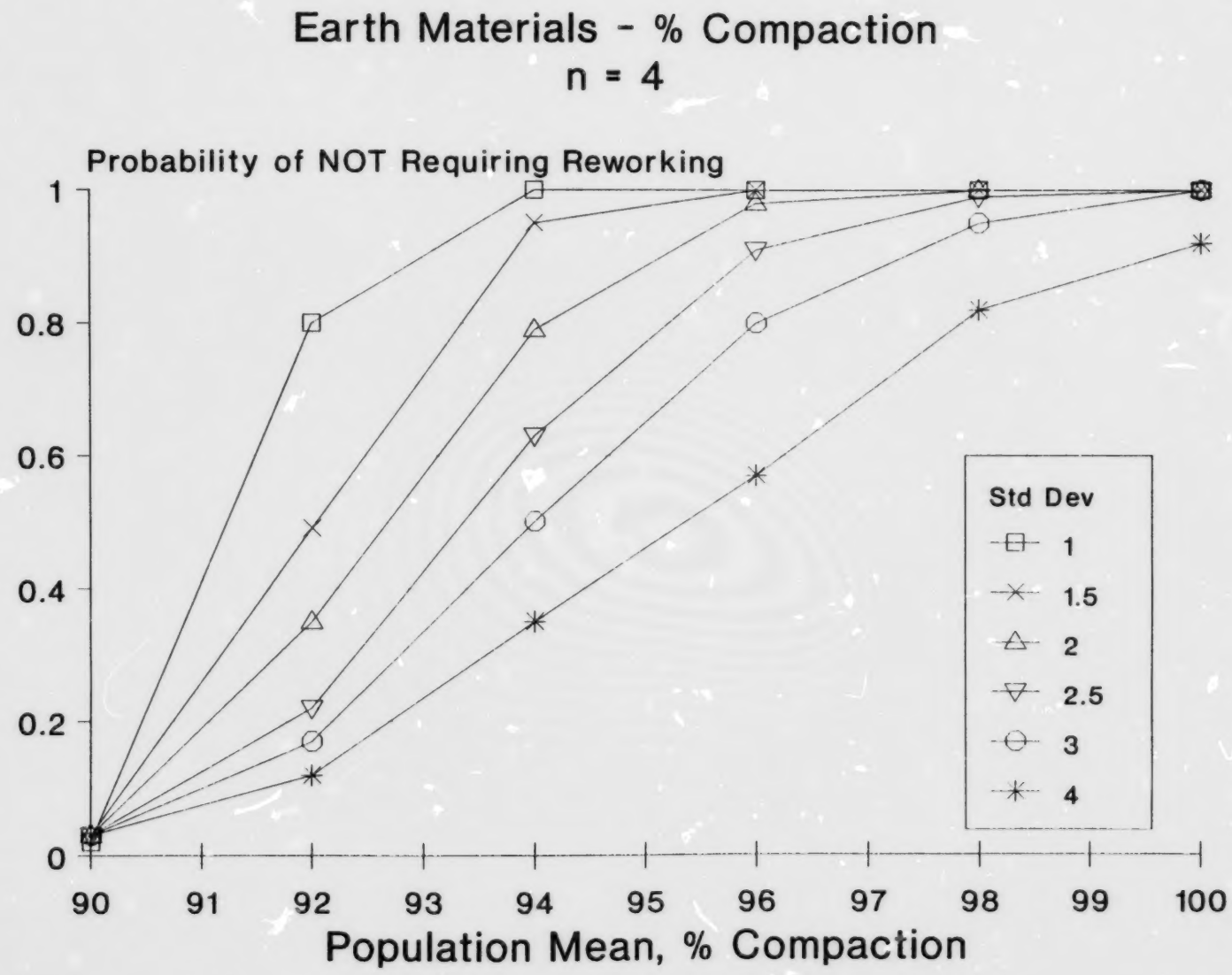


FIGURE 1. OPERATING CHARACTERISTICS FOR PERCENT COMPACTION FOR EARTH MATERIALS

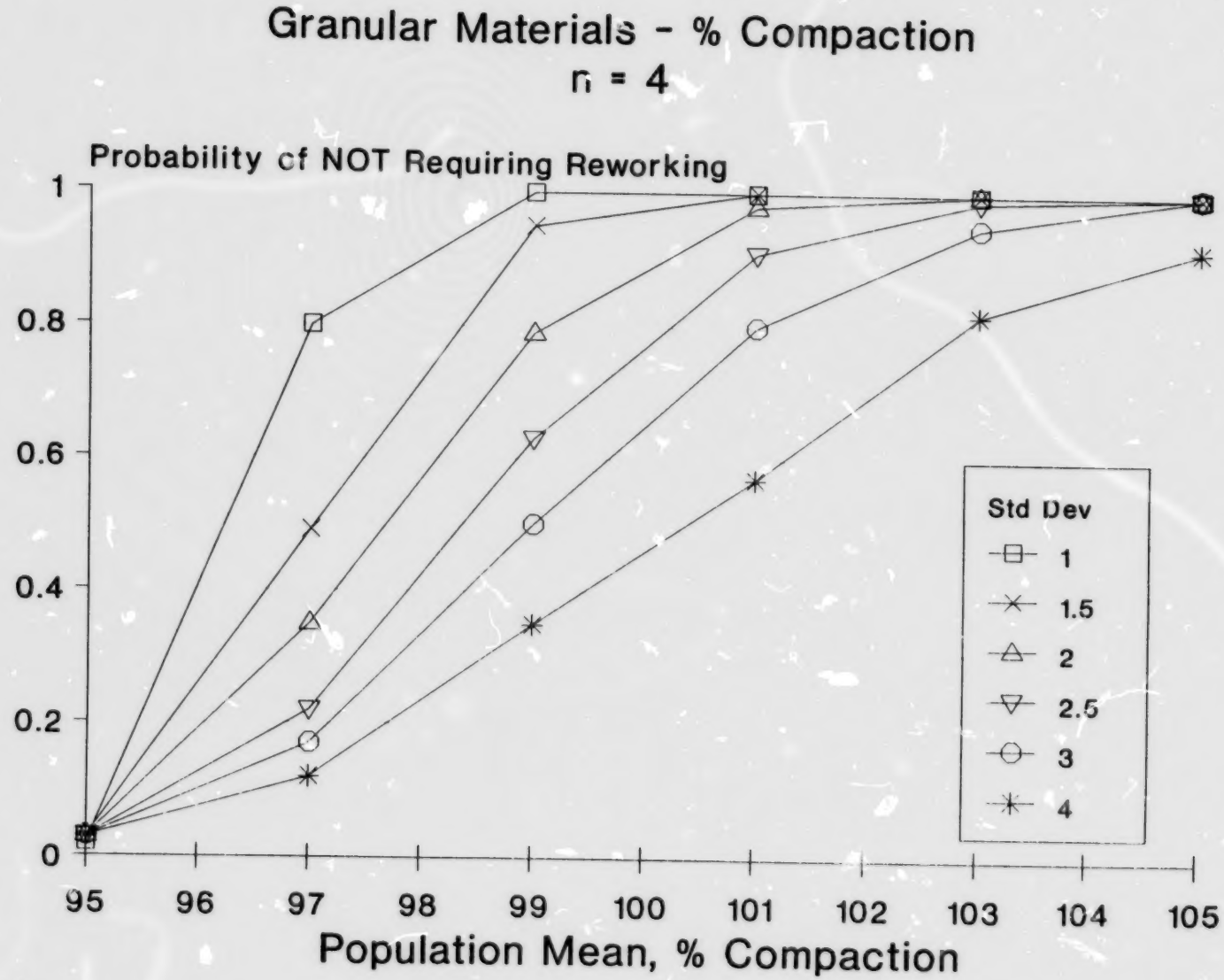


FIGURE 2. OPERATING CHARACTERISTICS FOR PERCENT COMPACTION FOR GRANULAR MATERIALS

value exceeds 96 percent for earth materials and 101 percent for granular materials. For a σ of 3.5 percent, a population mean of over 100 percent for earth materials and over 105 percent for granular materials, will be necessary to ensure that essentially no reworking is required.

Sieve Analysis

Computer simulation was used to develop separate OC curves for percent passing for each of the sieves for Granular A and Granular M material as listed in "Testing of Soils & Aggregates." The curves were based upon the assumption that the process could be represented by a normal distribution. The sieves were simulated individually, and no consideration was given to the possibility that there could be some correlation among the percent passing results for the various sieves. Ministry Report EM-39 and the Public Roads (1) articles were used to establish a range of standard deviation values to represent the process variability for each of the sieves.

19 mm Sieve - Granular A Material. OC curves for various standard deviations for the 19 mm sieve for Granular A Material are shown in Figure 3. In the simulation, values for percent passing that were greater than 100 were assigned values of 100. It was also assumed that a population mean of 100 was only possible if all of the material in the lot passed the sieve. Therefore, a mean value of 100 percent passing implied a σ value of zero, and the curves for all σ values were assigned 100% expected payments for a population mean of 100 percent passing.

For the smaller σ values, there is very little payment reduction indicated until the population mean reaches the lower acceptance limit. This probably indicates that the price adjustments are associated only with the mean and that the Range values are within the acceptable limits. For the larger σ values, the larger price adjustments are probably due to the fact that the sample ranges as well as the sample means are falling outside of the allowable limits.

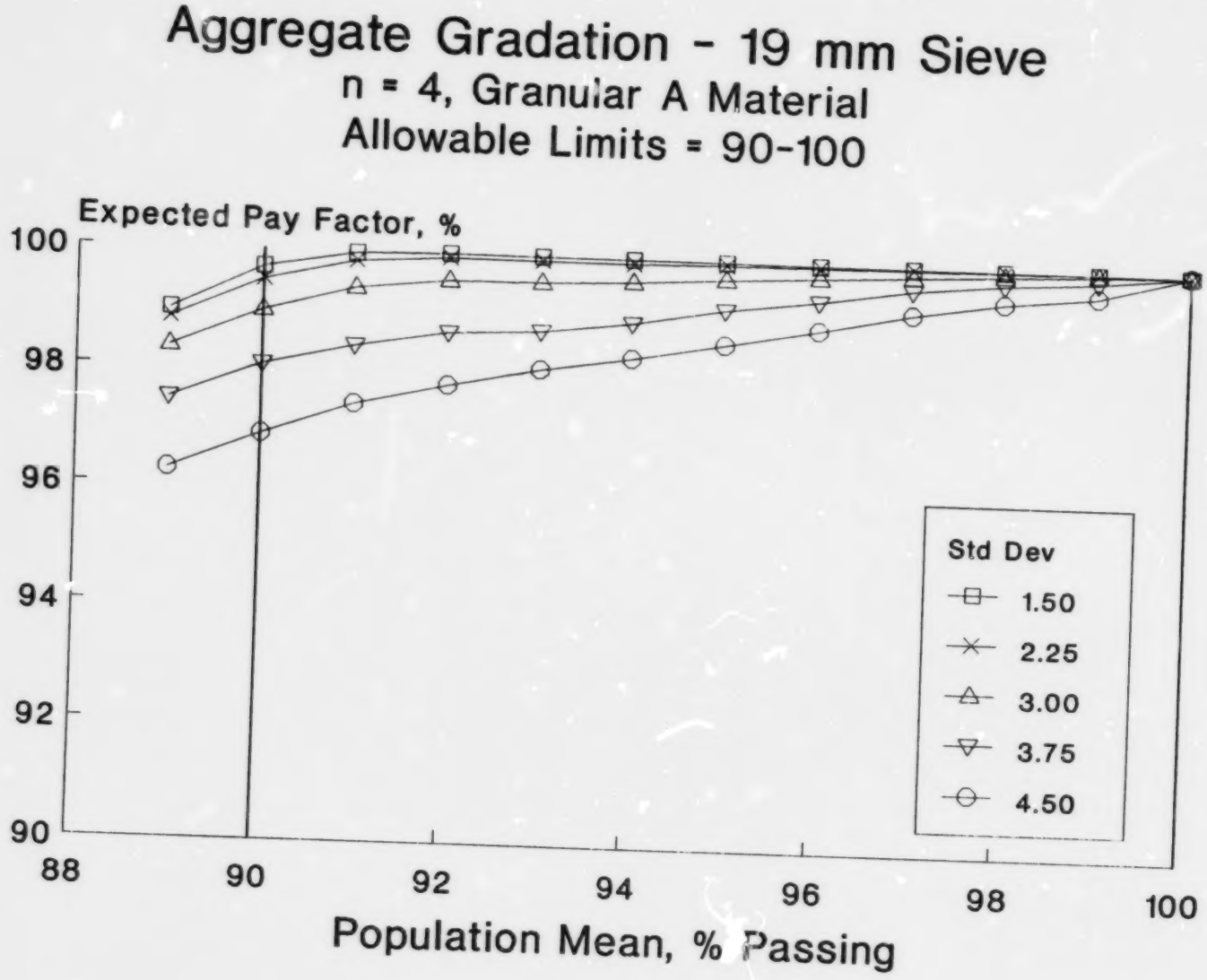


FIGURE 3. OPERATING CHARACTERISTICS FOR PERCENT PASSING FOR GRANULAR A MATERIAL FOR 19 mm SIEVE

13.2 mm Sieve - Granular A Material. Figure 4 presents the OC curves for the 13.2 mm sieve for Granular A Material. For the standard deviations simulated, there are essentially no payment reductions until the population mean reaches the upper and lower acceptance limits. The slight spread in the expected payment values at the acceptance limits is due to the difference in the σ values that lead to more sample means falling further below or above the allowable limits. Once the population means extend beyond the acceptance limits there is no difference in the expected payment results for the σ values simulated. This indicates that for this range of σ values all of the payment reductions were attributed to the sample means and little, if any, price reduction was due to the sample Ranges. This is because the allowable range limits are relatively wide in comparison with the σ values that were simulated. The σ values simulated cover the range of values obtained in Ministry Report EM-53 for the 16.0 mm sieve. There were no data in the report for 19.0 mm sieves.

13.2 mm Sieve - Granular M. Material. Figure 5 presents the OC curves for the 13.2 mm sieve for Granular M Material. The results are similar to those for Granular A in Figure 4, with the exception that the narrower acceptance limits for both mean and range combine to introduce a small expected payment reduction for population means within the allowable limits when the σ value is 4.50 percent passing.

A point of note that is present for both Figures 4 and 5, but that is more noticeable in Figure 5, is that for population means that are in a certain range outside the allowable limits (e.g., 98 percent passing), the expected payment is higher for populations with larger σ values. This is true because the wider spread of these populations makes it more likely to obtain sample averages that are within the allowable limits. This higher likelihood of an acceptable sample mean offsets the higher chance of the sample range exceeding its allowable limit.

9.5 mm Sieve - Granular A Material and Granular M Material. Figures 6 and 7 present the OC curves for the 9.5 mm sieve for Granular A Material and Granular M Material, respectively. The

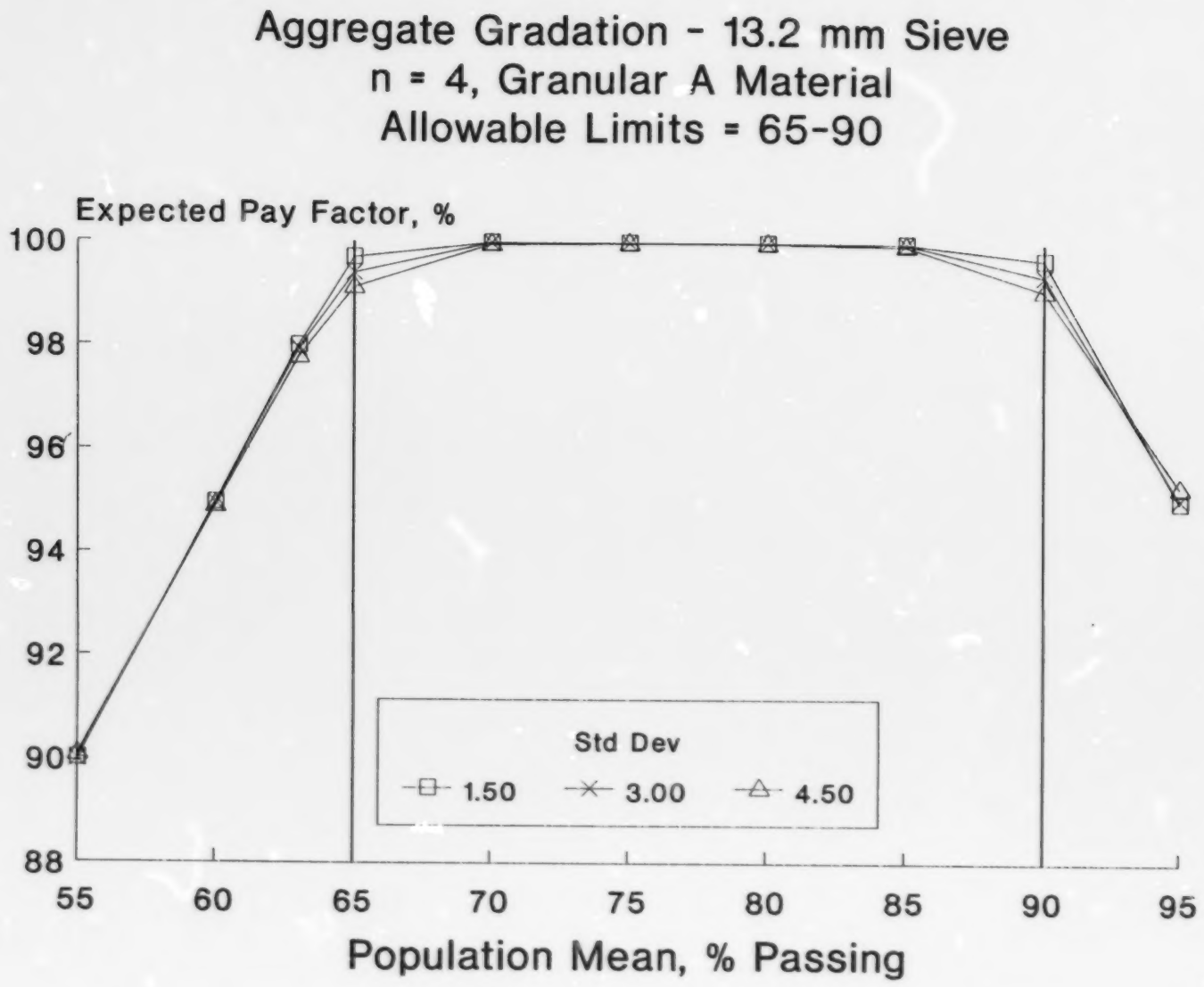


FIGURE 4. OPERATING CHARACTERISTICS FOR PERCENT PASSING FOR GRANULAR A MATERIAL FOR 13.2 mm SIEVE

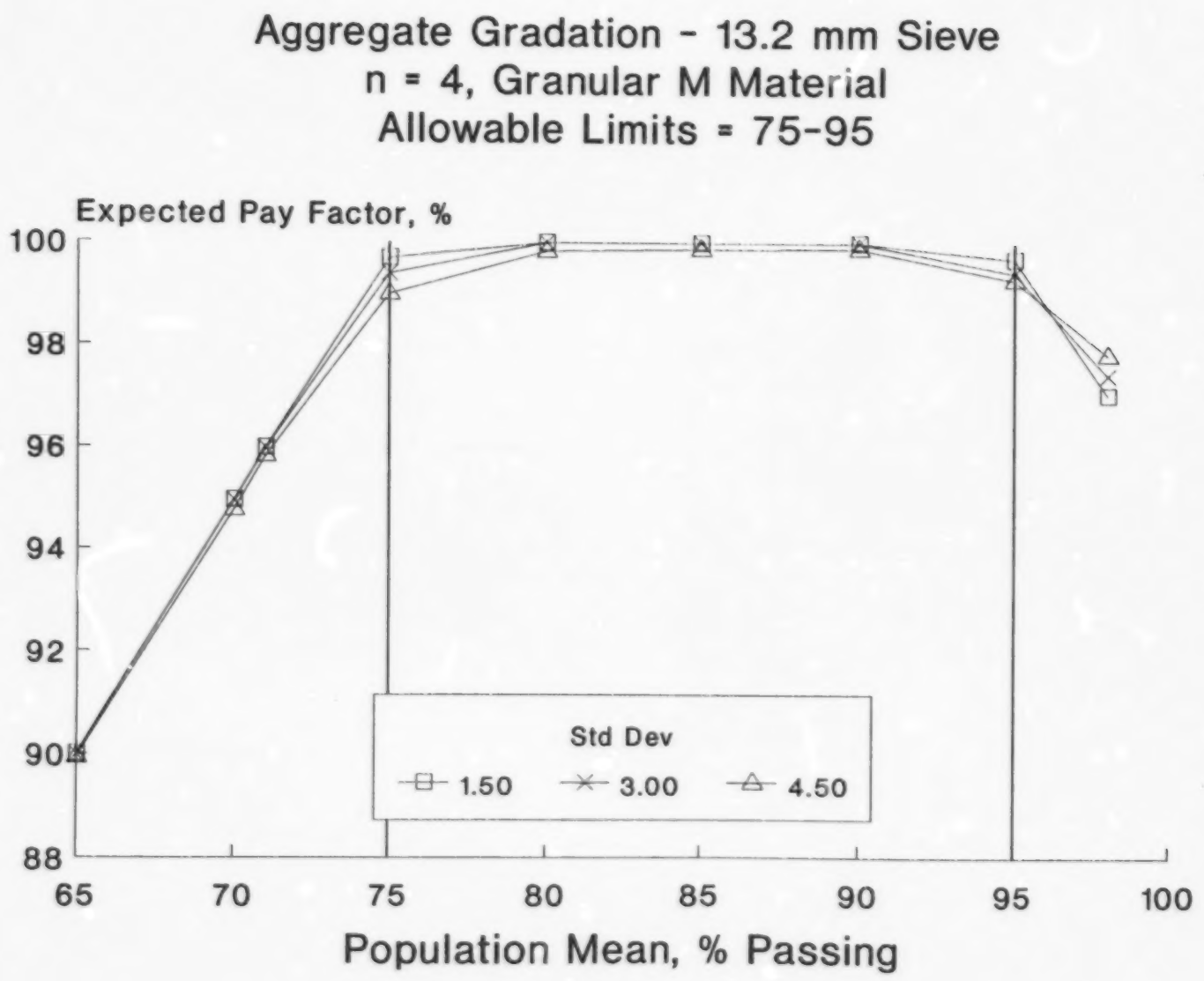


FIGURE 5. OPERATING CHARACTERISTICS FOR PERCENT PASSING FOR GRANULAR M MATERIAL FOR 13.2 mm SIEVE

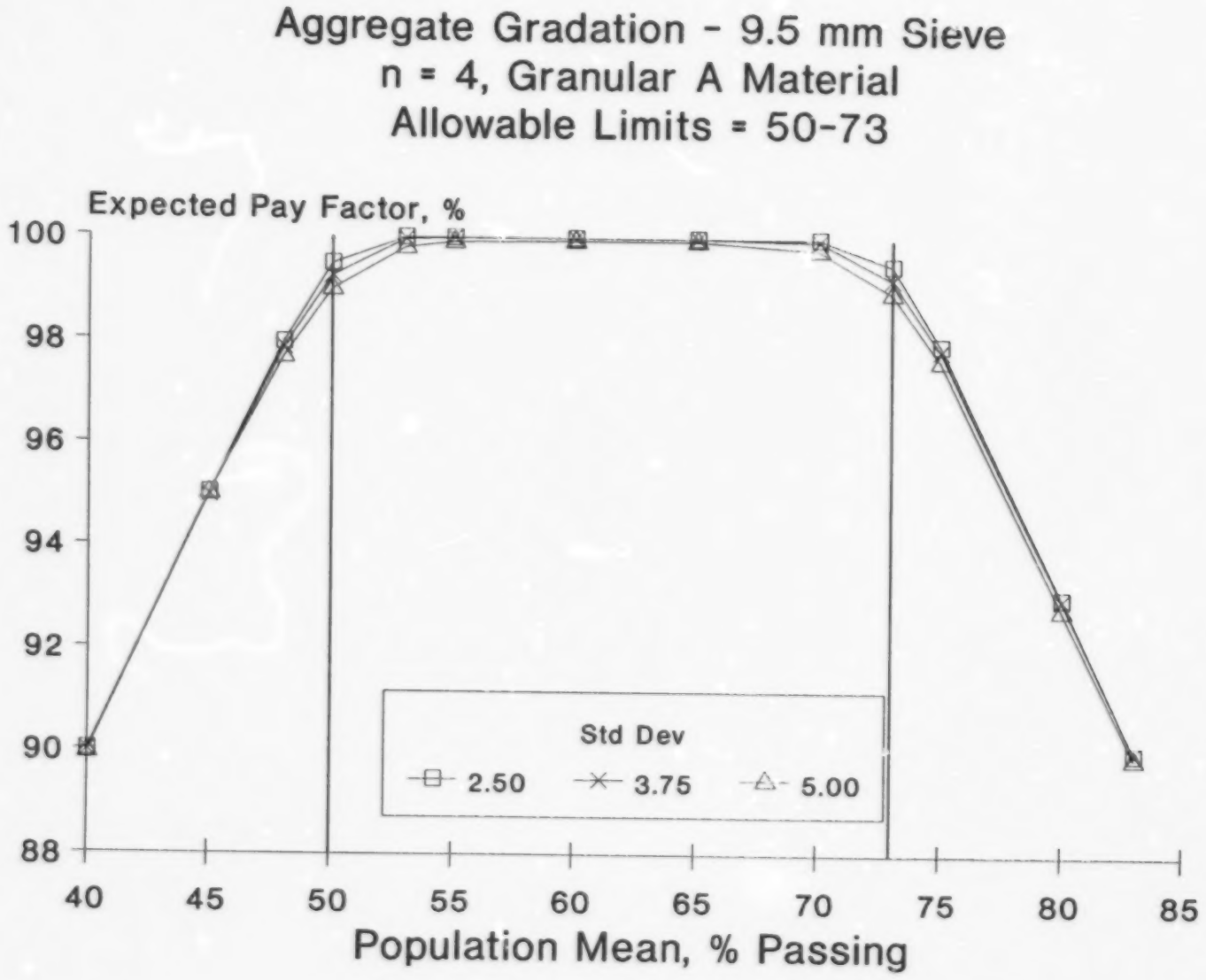


FIGURE 6. OPERATING CHARACTERISTICS FOR PERCENT PASSING FOR GRANULAR A MATERIAL FOR 9.5 mm SIEVE

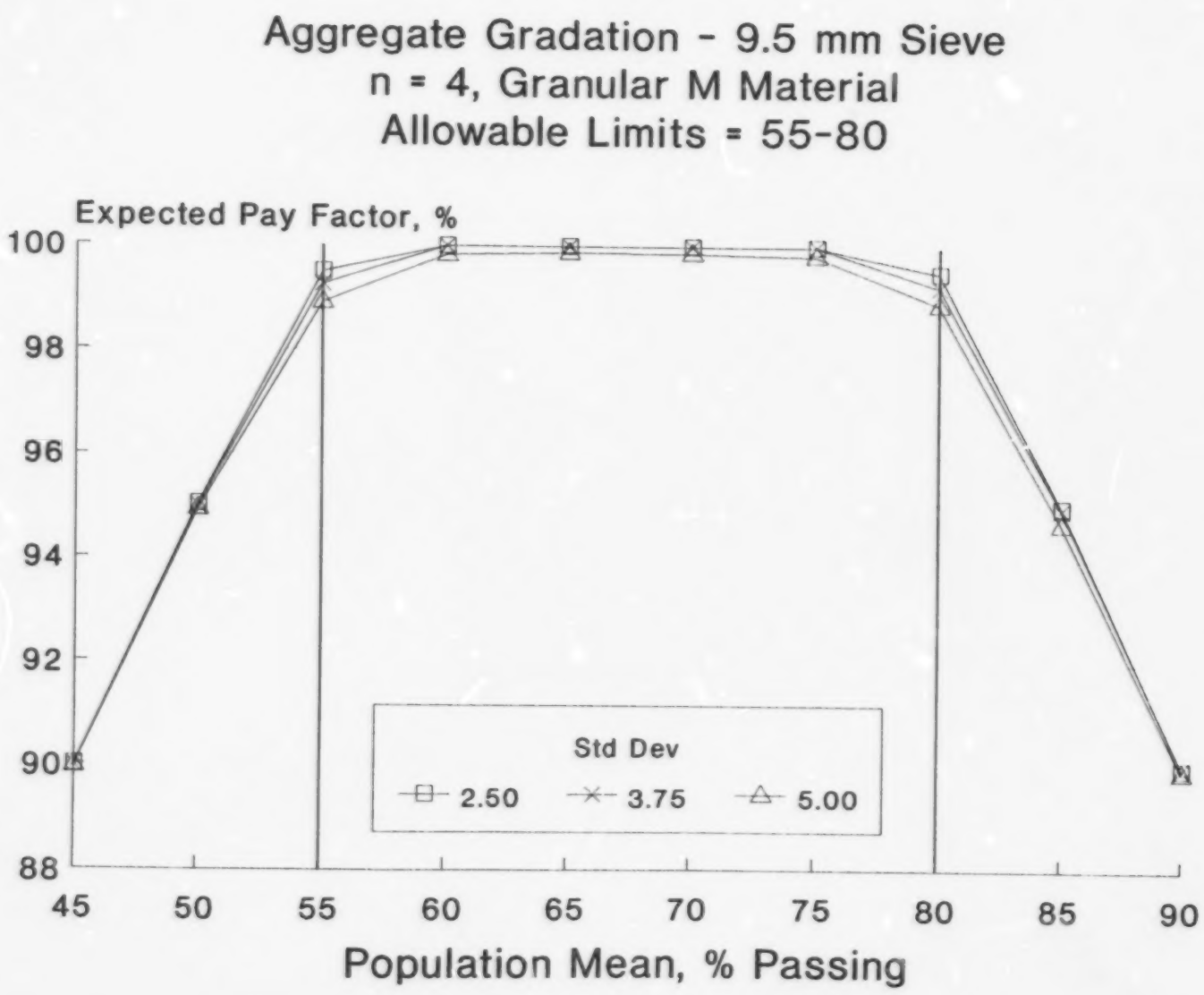


FIGURE 7. OPERATING CHARACTERISTICS FOR PERCENT PASSING FOR GRANULAR M MATERIAL FOR 9.5 mm SIEVE

same comments made above for the 19 mm and 13.2 mm sieves are appropriate for the 9.5 mm sieves

4.75 mm Sieve - Granular A & M Materials. OC curves for various σ values are presented in Figure 8 for the 4.75 mm sieve for Granular A & M Materials. The fact that the adjustment points factor for the 4.75 mm sieve is 2.5 times greater for excess passing the sieve than it is for insufficient passing the sieve is evident in Figure 8. The reason that the expected payment is so low for material on the high side of the allowable limits is that the specifications call for removal of the material when the price reduction exceeds 25 percent. During the simulation, lots with payment adjustments in excess of 25 percent were assumed to receive zero payment since they would require removal. This causes the expected payment to drop rapidly as the population mean percent passing exceeds the allowable acceptance limits.

1.18 mm Sieve - Granular A & M Materials. Figure 9 presents the OC curves for various σ values for the 1.18 mm sieve for Granular A & M Materials. The results are similar to those for the 19 mm, 13.2 mm and 9.5 mm sieves.

300 μm Sieve - Granular A & M Materials. Figure 10 presents the OC curves for various σ values for the 300 μm sieve for Granular A & M Materials. The results are similar to those for the 19 mm, 13.2 mm, 9.5 mm and 1.18 mm sieves.

75 μm Sieve - Granular A & M Materials. Figure 11 presents the OC curves for various σ values for the 75 μm sieve for Granular A & M Materials. The results clearly show the fact that the payment adjustment point factors for this sieve are 10 times greater than for the 19 mm, 13.2 mm, 9.5 mm, 1.18 mm and 300 μm sieves. The results are closer to those for the 4.75 mm sieve which has adjustment point factors that are only half and quarter those for the 75 μm sieve.

Simulated lots with payment reductions in excess of 25 percent were assumed to receive zero pay. As the population means extend outside the allowable limits by 1 percent (i.e, means of 1 and 9), the expected payment drops to 90 percent. For a population

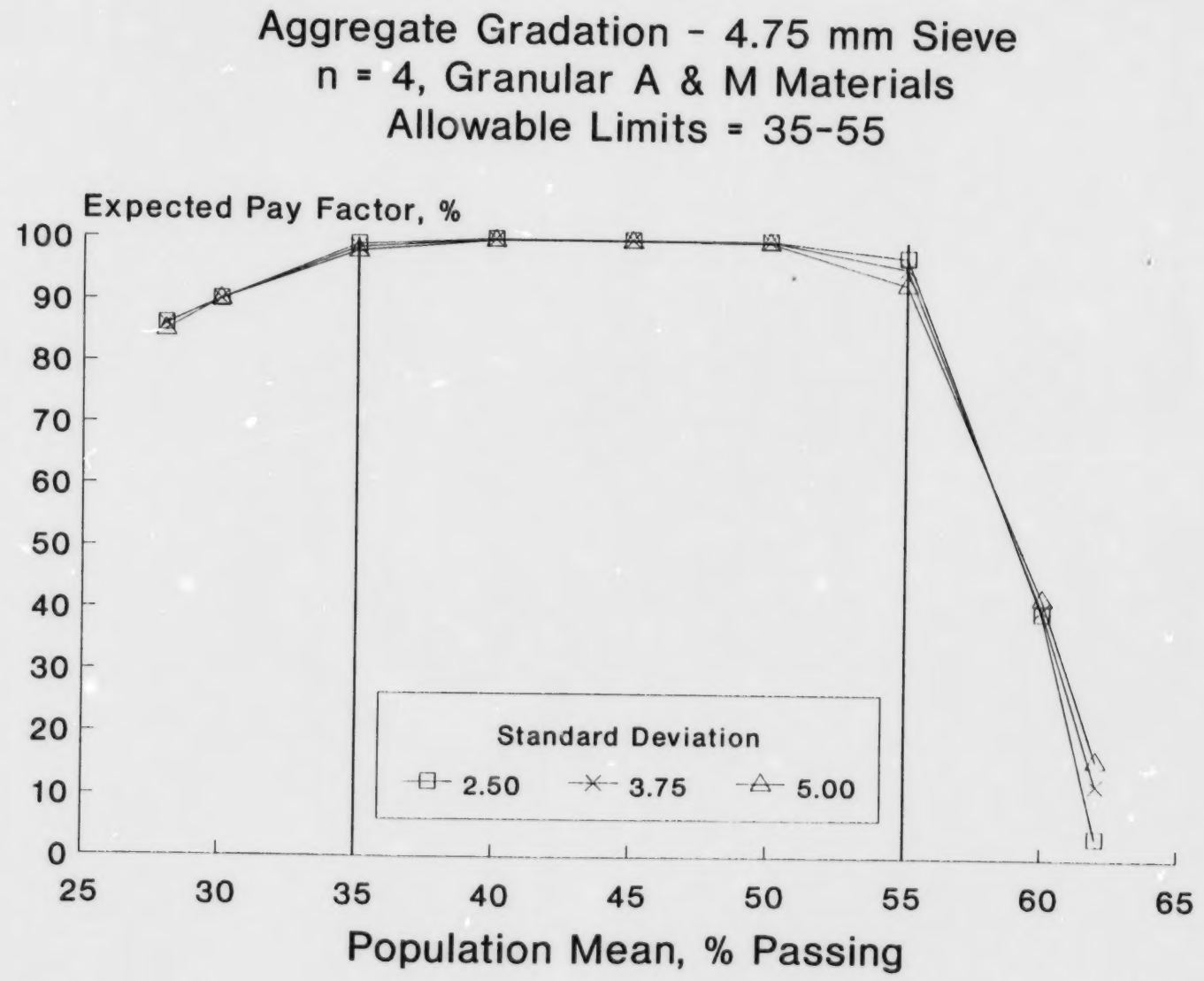


FIGURE 8. OPERATING CHARACTERISTICS FOR PERCENT PASSING FOR GRANULAR A &M MATERIAL FOR 4.75 mm SIEVE

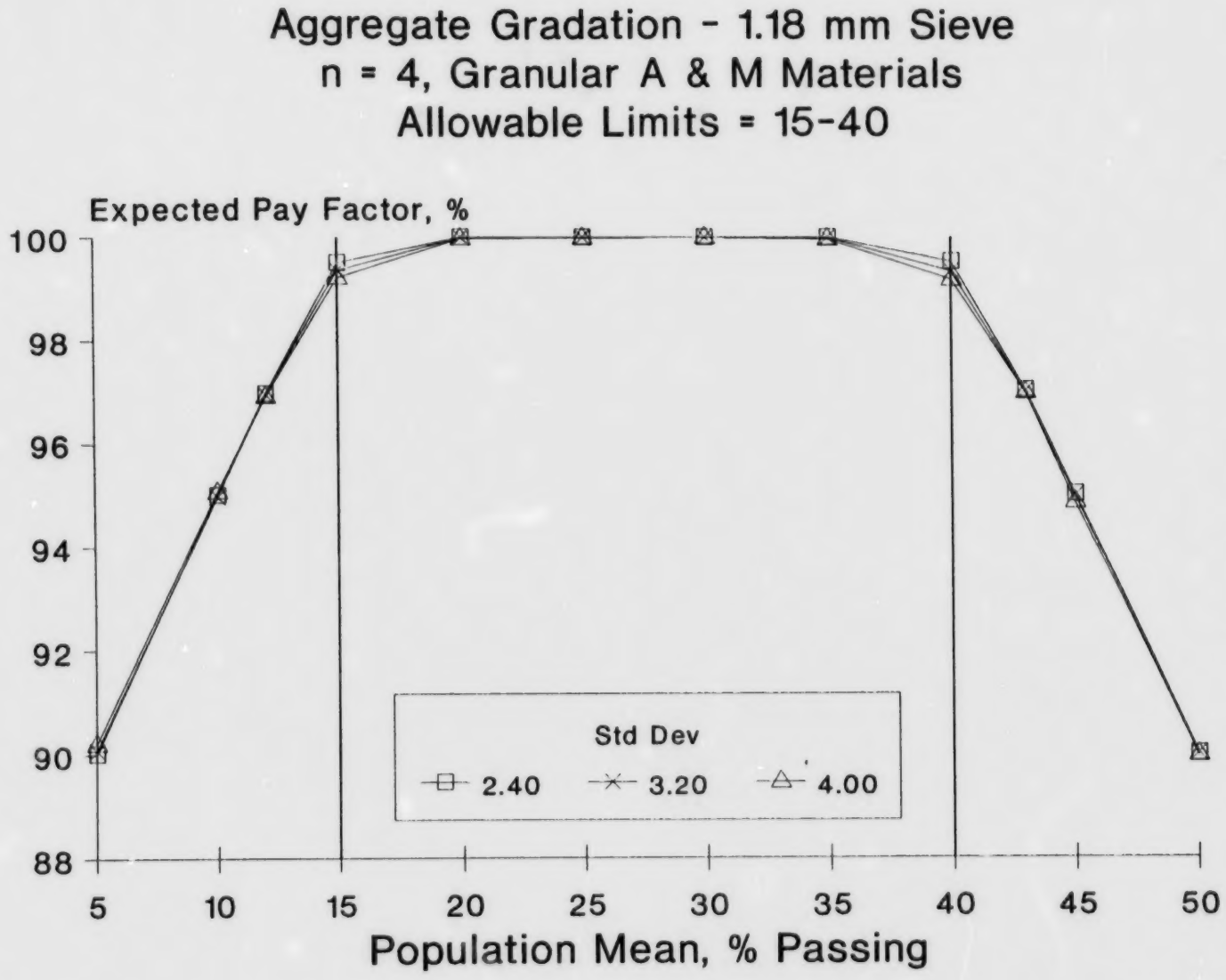


FIGURE 9. OPERATING CHARACTERISTICS FOR PERCENT PASSING FOR GRANULAR A &M MATERIAL FOR 1.18 mm SIEVE

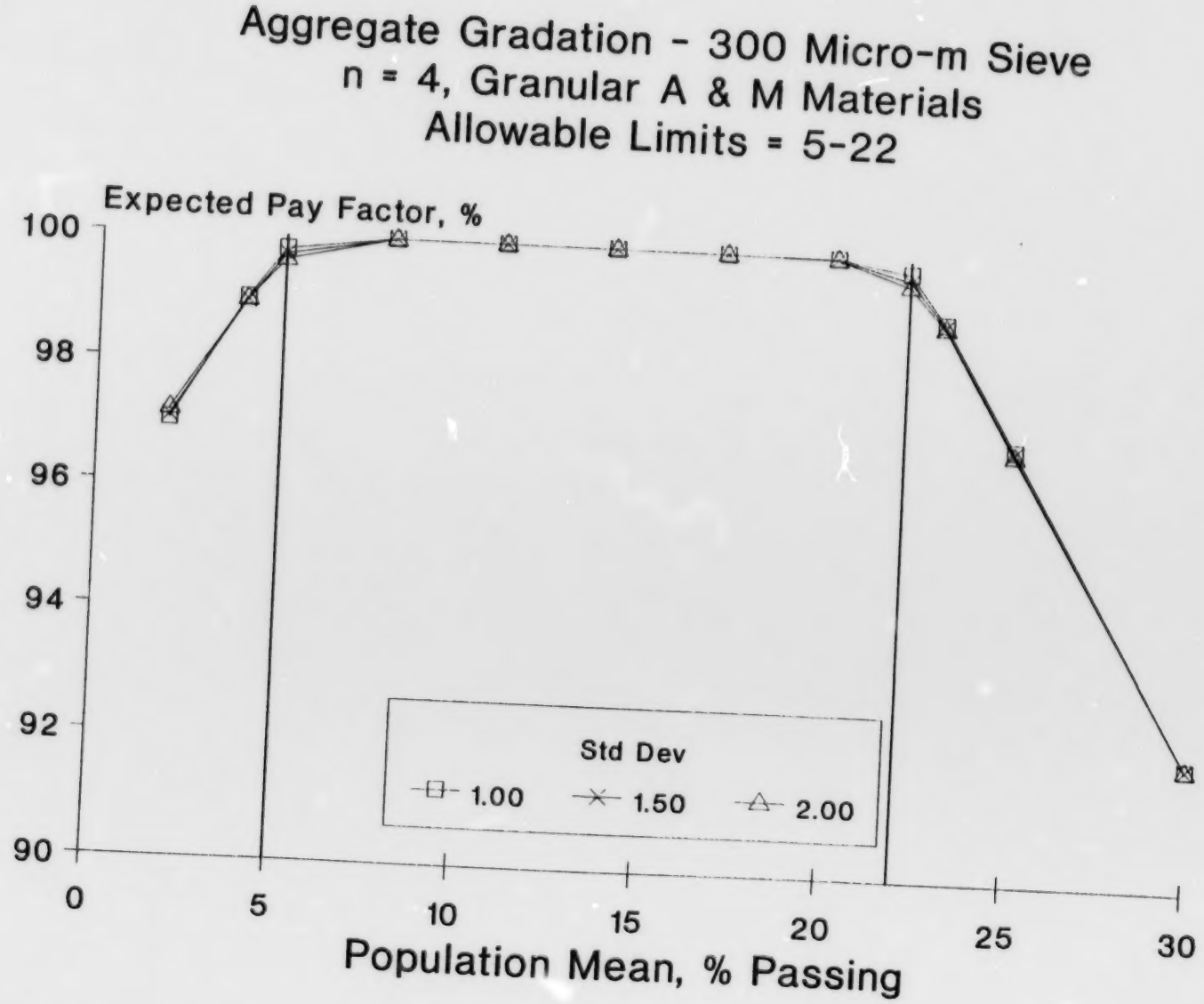


FIGURE 10. OPERATING CHARACTERISTICS FOR PERCENT PASSING FOR GRANULAR A & M MATERIAL FOR 300 μm SIEVE

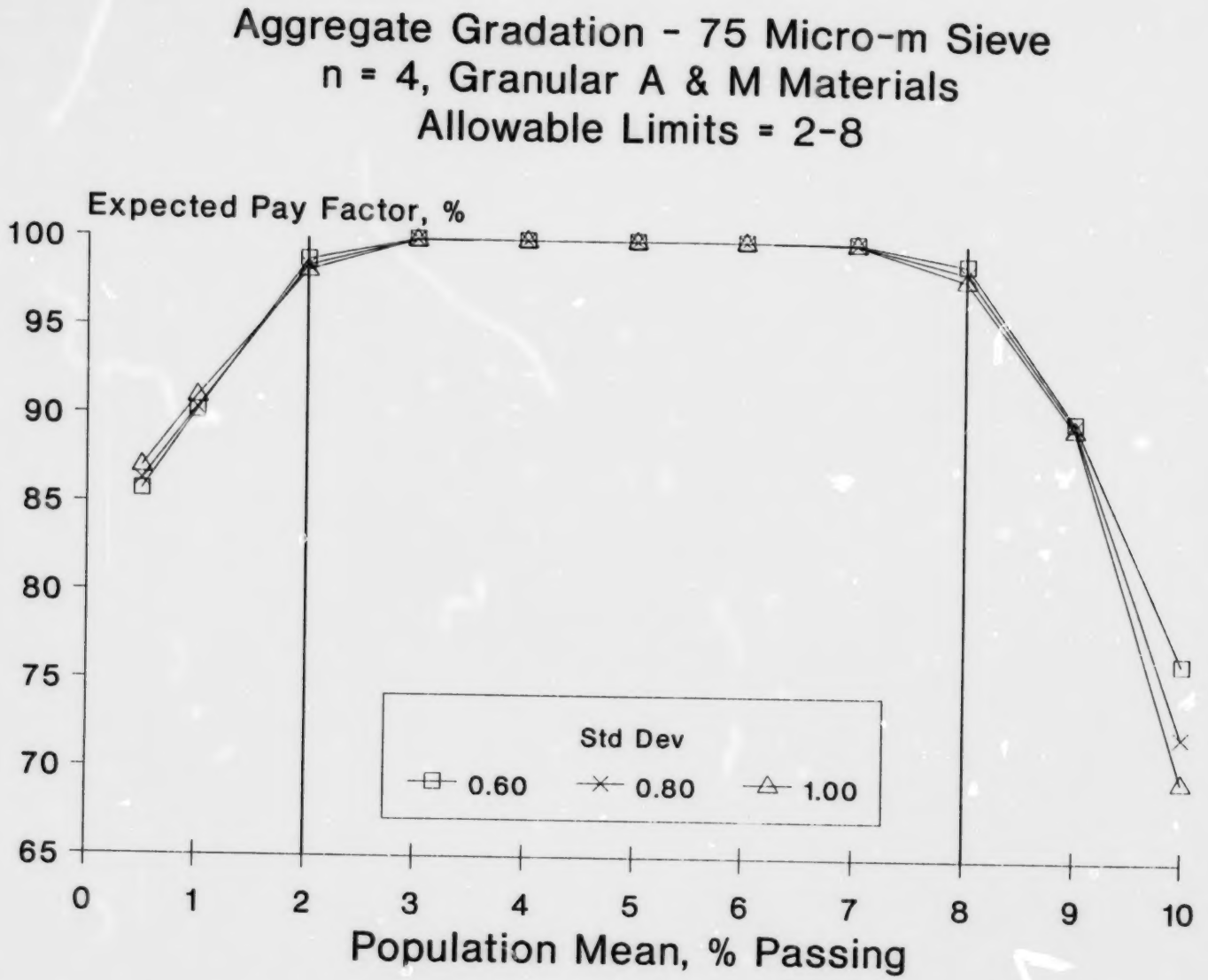


FIGURE 11. OPERATING CHARACTERISTICS FOR PERCENT PASSING FOR GRANULAR A & M MATERIAL FOR 75 μm SIEVE

mean of 10 percent passing (i.e., 2 percent above the allowable limits), the expected payment drops to between 70 and 76 percent.

General Comments on the OC Curves

Compaction of Granular and Earth Materials. The OC curves in Figures 1 and 2 indicate that the acceptance procedures generally perform as intended, with the contractor encouraged to provide material with higher mean compaction and lower variability in order to reduce the expected reworking required. However, due to the relatively small sample size (i.e., n = 4), the fact that the sample range is used rather than the sample standard deviation, and the fact that a very high population PWL value is required, there are reasonably high risks involved.

For example, a population (lot) of earth material with mean of 96 percent compaction and standard deviation of 2.5 has an actual PWL of 99.2. This lot should therefore be accepted since it meets the minimum 99 PWL requirement. However, the OC curves in Figure 1 indicate a probability of not requiring rework of only approximately 0.9. Also, a population with mean of 92 and standard deviation of 1 has an actual PWL of 97.7, and should require reworking. However, Figure 1 indicates a probability of not requiring rework of 0.8.

Sieve Analysis. In general, for the σ values used in the simulations, there appear to have been few payment reductions associated with sample ranges exceeding the allowable limit. Since the σ values simulated were obtained from data obtained from the Ministry as well as from outside sources (1), **if** current production is similar to that on which the data were collected, it would seem that the allowable Range requirements should not be difficult to meet.

For the sieves that have a 0.1 payment adjustment point factor (i.e., 19 mm, 13.2 mm, 9.5 mm, 1.18 mm and 300 μm) the expected payment is nearly 100 percent provided the population mean is within the allowable limits. For the other sieves, the 4.75 mm and the 75 μm, the expected payments are nearly 100

percent while the population mean is within the allowable limits, but decrease rapidly as the limits are exceeded only slightly.

A review of the OC curves in Figures 3 through 11 indicates that the present acceptance plan provides a strong incentive for the contractor or supplier to maintain the process mean within the allowable limits for the 4.75 mm and 75 μm sieves. If a supplier maintains control on these sieves, then the likelihood of a significant price reduction is slim for the other sieves combined.

The acceptance procedures appear to work as the Ministry intended. Since there appear to be few, if any, price adjustments resulting from excessive Range values, the expected payments are as expected from the payment schedule. That is, the expected price reductions from the simulations are generally equal to the adjustment points for the sieve size multiplied by the absolute difference between the population mean and the acceptance limit. For example, for Granular A material, 75 μm sieve, a percent passing value of 9% should have a payment of 90%. Figure 11 indicates an expected payment value of 90% for a population mean percent passing of 9%.

CHAPTER 3 - CONCRETE MATERIALS

INTRODUCTION

The information reviewed in the Concrete area was from the following documents:

> Special Provision No.113S04, "Concrete Mix and Strength," December, 1988.
>
> Draft Special Provision, "Concrete Pavement, Concrete Base, Lean Concrete Base, Load Transfer Devices," 89 01 12.

In addition, supporting information in the following report was reviewed as a source of variability data:

> "Development of Special Provisions for the Acceptance of Lean Concrete Base, Concrete Base, and Concrete Pavement," Report MI-76, Materials Information, Engineering Materials Office, Ontario Ministry of Transportation and Communications, March, 1985

The review was conducted only with respect to the statistical aspects of the acceptance procedures.

GENERAL COMMENTS

The following comments relate to the review of the statistical aspects of the above materials relating to concrete. The comments are presented individually, and, where appropriate, suggestions or recommendations are presented.

Concrete Mix and Strength

1. Based on correspondence with Mr. Roger Northwood, the acceptance limit and lot sizes were based on practices that had been in effect for many years prior to the development of the statistically-based acceptance procedures. This is a logical approach to take when implementing new procedures, and is one that should facilitate quicker acceptance of the procedures by contractors and suppliers. The acceptance procedures incorporate both the mean and the standard deviation thereby considering the important concept of variability.

2. Also based on correspondence with Mr. Northwood, the price adjustment equation was developed based on equating the price reduction for being 2 MPa below the specified strength to the supplier's expected profit of about $10 on concrete with a delivered price of $80. This approach for determining the price reduction will necessarily require the payment determination equation to be updated periodically to reflect increases in delivered concrete prices.

The 2 MPa level is based on results from prior projects, i.e., past experience. Even though this is a common approach when developing specifications, if there are no performance justifications for arriving at this number, there is the possibility that a contractor or supplier may claim the level was arbitrary and should not be enforced since it is a penalty.

The approach for determining the price adjustment also assumes that the contractor will always pass on the price adjustment to the supplier. There could be times when the contractor's construction practices or scheduling could contribute to low concrete strength. However, the assumption that the price adjustment will be passed on to the supplier is probably correct in nearly all cases.

3. The Special Provision indicates that the Ministry will calculate the mean and standard deviation and forecast potential price reductions, and supply the contractor and concrete supplier with an analysis of the test results at monthly intervals. Mr. Northwood indicated that the monthly interval was adopted to cut down on formal paperwork. If price reductions are involved, it is probably preferable to notify the contractor and supplier immediately. A great deal of material can be placed at risk during a month of production. A contractor or supplier is likely to want to know as soon as possible when price reductions are developing so that steps can be taken to revise the process to bring it back within the specification requirements.

Concrete Pavement, Concrete Base, Lean Concrete Base

1. Payment for strength is based strictly on sample mean. This ignores the important property of material variability. Other Ministry acceptance procedures that are reviewed in this report incorporate variability by means of accepting on both averages and ranges or by accepting on PWL. The acceptance criterion for concrete mix strength also incorporates variability by including the sample standard deviation in the acceptance decision.

By not considering variability, lots with the following strength results would have the same level of acceptance:

Lot 1: 20 25 30 35 $\bar{X} = 27.5$ $\sigma = 6.5$

Lot 2: 27 27 28 28 $\bar{X} = 27.5$ $\sigma = 0.6$

While this is an extreme example, it illustrates that, while the two lots have the same mean, they have widely different variabilities, and hence do not have the same uniformity.

Acceptance by mean only assumes, implicitly, that the process standard deviation, i.e. variability, is constant. Since it is likely that process variance will vary from supplier to supplier and contractor to contractor, the use of the Range in addition to the mean (or, preferably, the use of PWL) should be considered. The effect of not considering variability in the acceptance decision is illustrated in the OC curves presented in subsequent sections of this report.

2. The provision allowing re-testing when the sample mean strength does not meet the required strength raises questions regarding the appropriate sample size. Re-testing can typically be viewed in two ways: the initial tests are invalid and should be discarded, or the initial tests are valid and should be added to the re-tests to double the original sample size. The re-testing allowed in the Special Provision creates some difficulties because the re-tests are from a population that has had additional time to

age and should therefore have a higher mean strength. This would tend to argue against pooling the initial tests and the re-tests.

It could be reasoned that if the population has changed due to additional aging that the original tests should not be used and that only the re-tests, representing the new population, should be used. However, the Special Provisions allow either set of tests to be used for the acceptance decision, depending upon the results of the re-tests. It would seem that a more rational approach might be to use the re-test results if they are higher than the original tests by some stated amount (the current Special Provisions requirement is 5%), otherwise, the average of both the original tests and re-tests could be used. If variability, by way of Range or PWL, is added to the acceptance procedures, then the acceptance limits would have to be adjusted for the increased sample size associated with pooling the test results.

3. Correspondence from Ms. Hannah Schell indicates that the price adjustment for slab thickness was established to be proportional to the magnitude of the difference between the calculated flexural strengths for the design thickness and the measured thickness. This appears to be a rational approach that is an attempt to correlate the price adjustment with the anticipated performance of the pavement.

The payment level for thickness is based on a continuous payment schedule established by an equation. This is preferable to a discrete, stepped payment schedule that may have large differences in payment associated with relatively small differences in the measured property.

4. Unlike thickness, the payment adjustment for strength is a discrete, stepped payment schedule. A continuous schedule, in the form of an equation, is usually preferable to a discrete schedule. For example, for concrete pavement, Table 3 on page 17 of the Draft Special Provisions indicate that a lot with a sample mean of 20.0 MPa would receive 94 percent payment, while a lot with a sample mean of 19.9 MPa would receive only 90 percent payment.

Correspondence from Ms. Schell included the plot shown in Figure 12(a) to indicate that the price adjustment table was established to be proportional to the strength reduction, with a maximum payment reduction of 10 percent. It should be possible to establish a continuous price adjustment schedule which accomplishes the same objectives as Figure 12(a) and which provides the same expected payment in the long run. Although the expected payment curves for the two schedules would be approximately the same, the continuous schedule would be preferred because it would avoid the potential problem of relatively large payment differences for relatively small differences in the measured strength.

Figure 12(b) is an example of a continuous schedule which should provide operating characteristics similar to those of the discrete payment schedule currently in the Draft Special Provisions. If the Ministry chooses to adopt a continuous payment schedule, then its OC curves could easily be developed to verify that it provides characteristics similar to the current schedule. A similar type of continuous schedule could be developed for Lean Concrete Base.

5. Adding the price reductions for strength and thickness essentially treats them as independent properties which are not correlated with one another. This is probably the most reasonable assumption. If, however, the Ministry believes that the two may be correlated in some way, then averaging the two price reductions might be considered as an alternative. This approach does not directly consider the fact that the two may be correlated, but it does not implicitly assume they are independent. As noted above, it seems reasonable to assume that strength and thickness are not correlated.

OC CURVES

OC curves were developed for **Concrete Mix Strength**, **Core Strength** and **Core Thickness**. In each simulation, 1000 lots were simulated with various population means and standard deviations

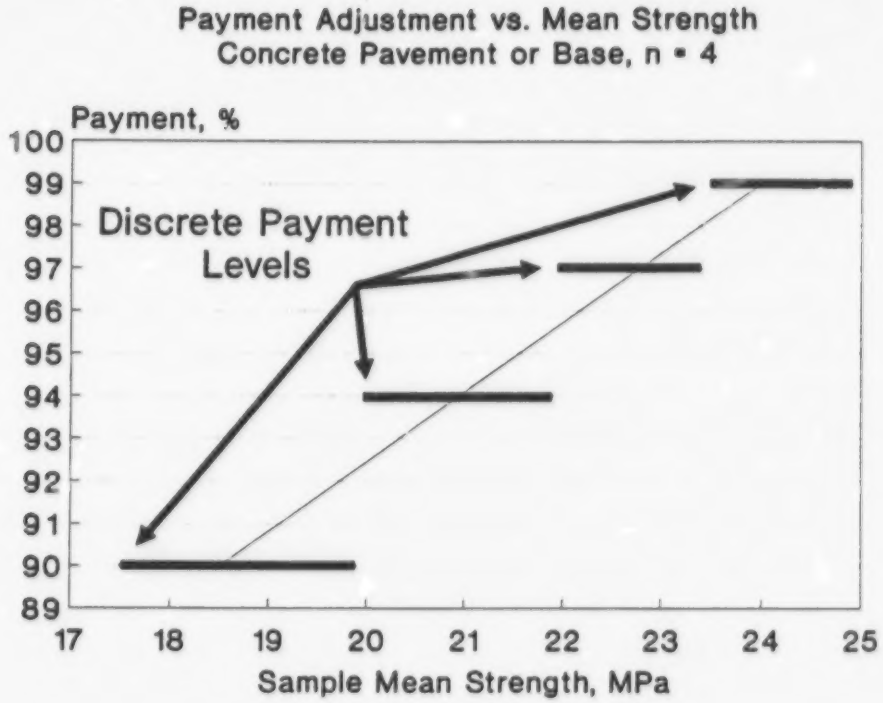


FIGURE 12(a). CURRENT DISCRETE PAYMENT SCHEDULE FOR CORE STRENGTH FOR CONCRETE PAVEMENT & BASE

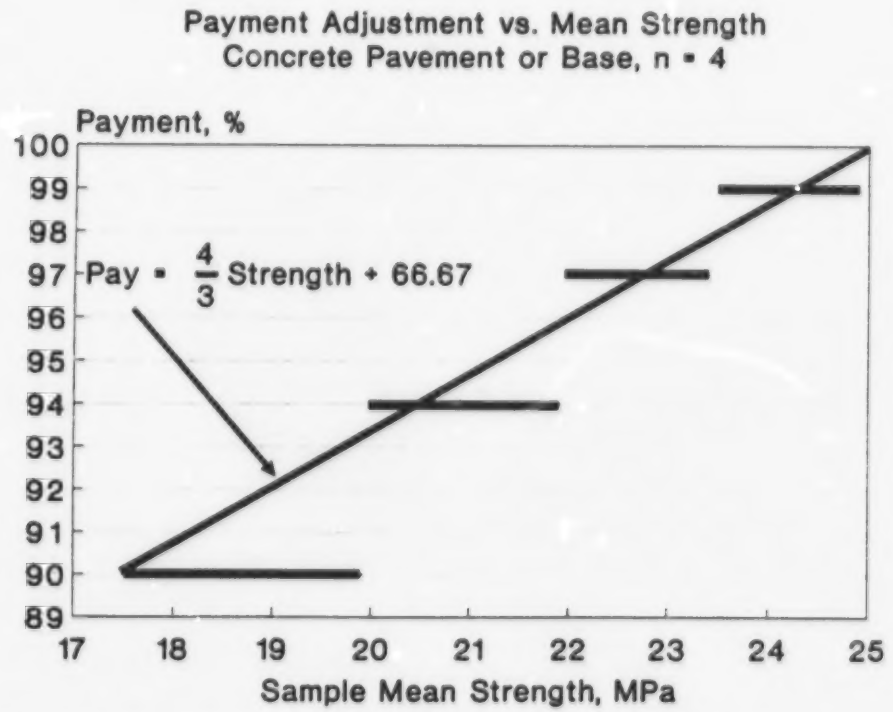


FIGURE 12(b). POSSIBLE CONTINUOUS PAYMENT SCHEDULE FOR CORE STRENGTH FOR CONCRETE PAVEMENT & BASE

(σ), and payment levels were determined in accordance with the appropriate acceptance requirements. The σ values used in the simulations were based on data from Ministry Report MI-76. The Public Roads (1) articles were also used in deciding upon which σ values to use. It was assumed that each of the properties could be satisfactorily represented by the normal distribution.

Concrete Mix Strength

Figure 13 presents the OC curves for concrete mix strength. The effect of different variabilities, i.e., σ values, is most pronounced at the specified strength of 30 MPa.

In Mr. Northwood's correspondence, he indicated that the price adjustment equation was established to have a price reduction of about $10 if the population mean strength were 2 MPa below the specified strength of 30 MPa. The population mean is the true mean of the lot produced by the contractor, and is estimated for payment determination purposes by a sample mean. The OC curves in Figure 13 show that for a population mean strength of 28 MPa the expected payment reduction varies from about $9 to $11 depending upon the value of the population σ. It would appear that the acceptance procedures will operate as planned by the Ministry. However, the supplier must maintain a relatively small population σ to avoid payment reductions at population means that are above, but near, the specified strength.

Core Strength

Figure 14 presents OC curves for Core Strength for Concrete Pavement and Concrete Base. The OC curves for Lean Concrete base are shown in Figure 15. Since the payment determination is based strictly on sample mean results, the OC curves show little distinction among the different values of σ. Little difference is found among the expected payments for the various σ values until the population mean begins to approach the 17.5 MPa limit that requires removal and replacement. Simulated lots with sample means < 17.5 MPa were assumed to receive zero payment.

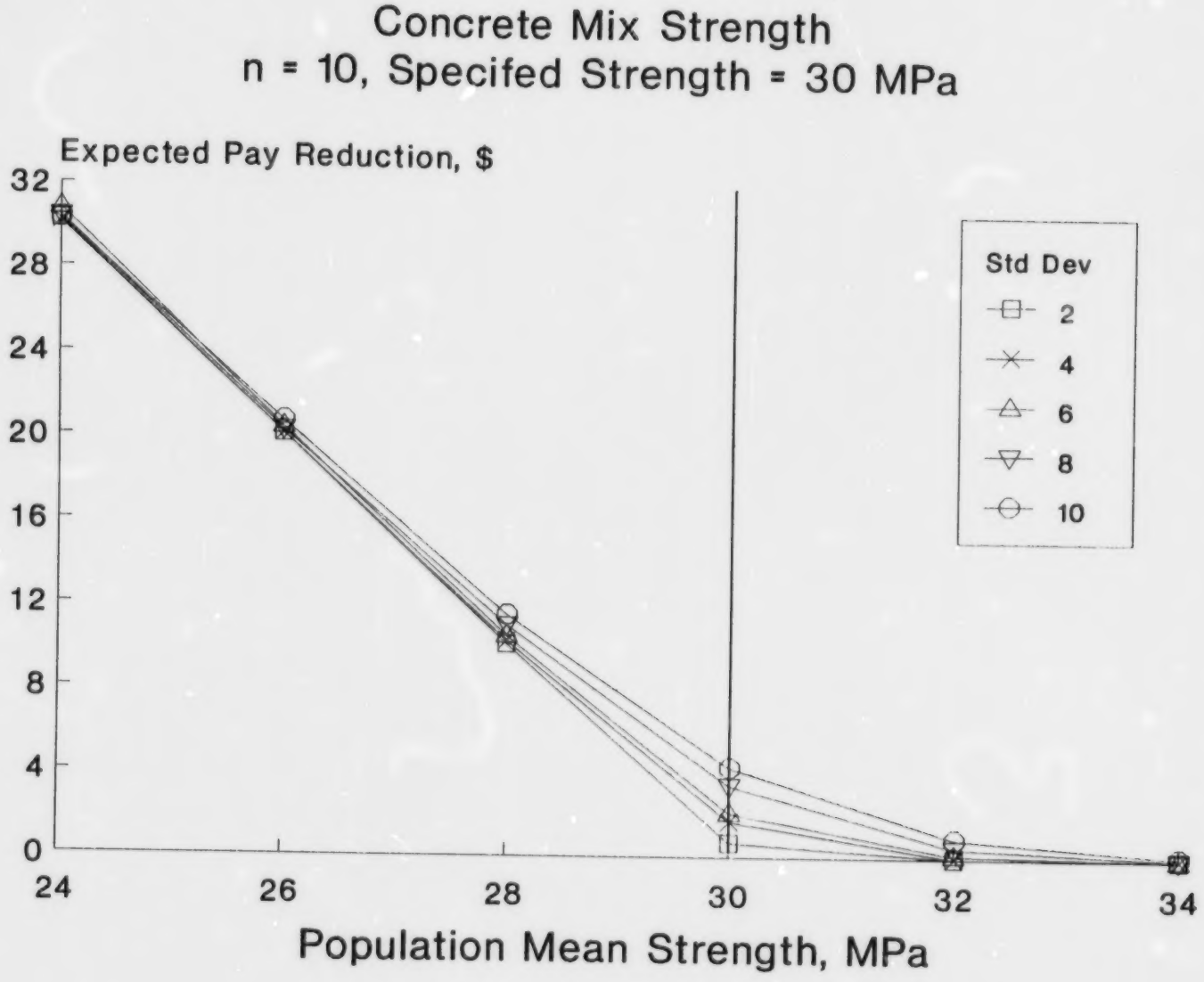


FIGURE 13. OPERATING CHARACTERISTICS FOR CONCRETE MIX STRENGTH

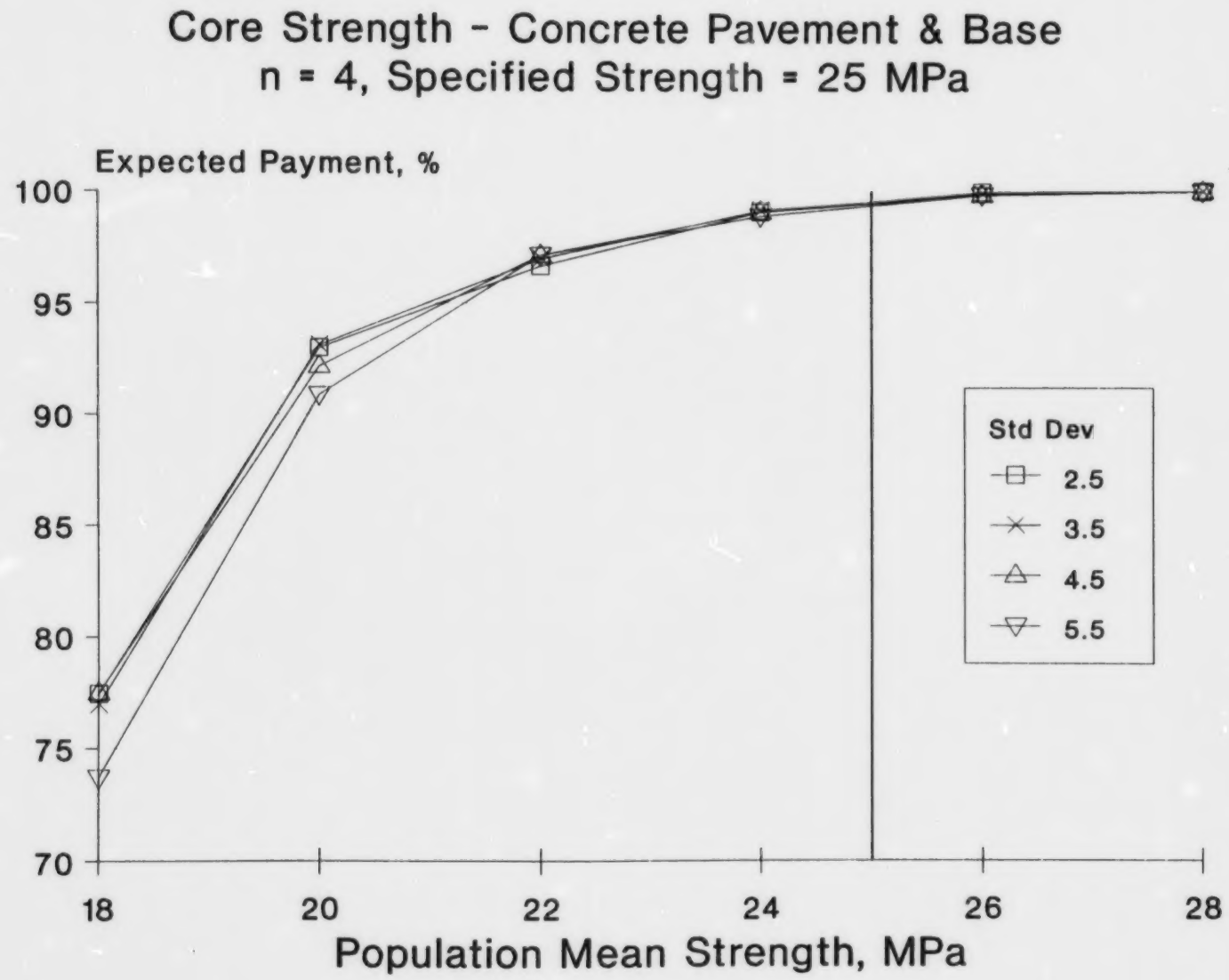


FIGURE 14. OPERATING CHARACTERISTICS FOR CORE STRENGTH - CONCRETE PAVEMENT & BASE

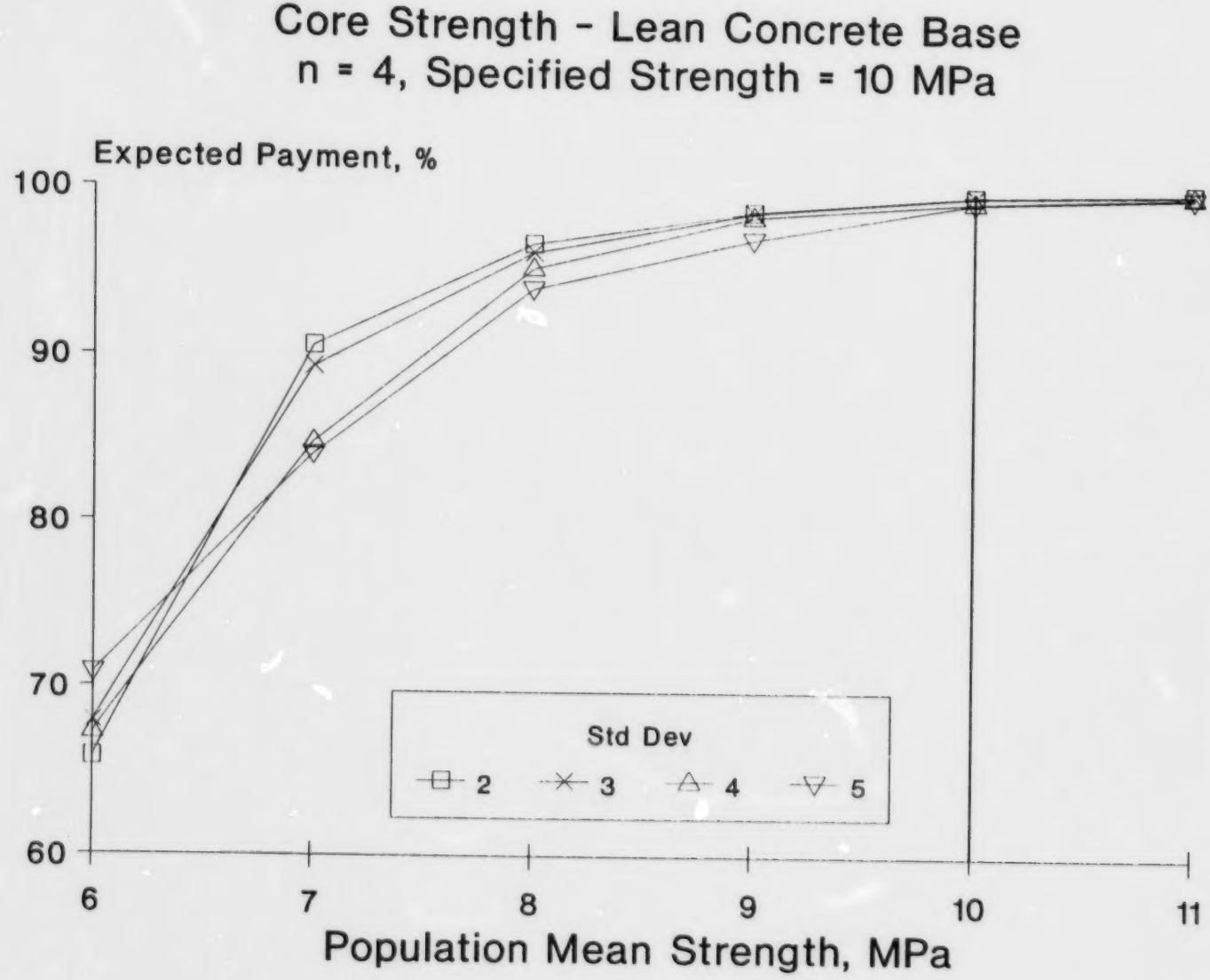


FIGURE 15. OPERATING CHARACTERISTICS FOR CORE STRENGTH - LEAN CONCRETE BASE

Since the σ values for Lean Concrete Base represent higher coefficients of variation, the effect of different σ values is more pronounced on the OC curves in Figure 15. It should be noted that, because acceptance is based on only the sample mean, the largest standard deviation in Figure 15 has the highest expected payment for a population mean of 6.0 MPa. This is due to the fact that the population with the larger standard deviation has a greater likelihood of yielding a sample mean that will exceed the specified strength of 10 MPa.

Core Length

Figures 16 through 18 present OC curves for core length for Concrete Pavement, Concrete Base and Lean Concrete Base, respectively. The specified core lengths used in developing the OC curves were taken from Ministry Report MI-76. Observation of the curves in Figures 16 through 18 illustrates that the expected payments become less when going from Concrete Pavement to Concrete Base to Lean Concrete Base. The primary reason for this trend is that the pavement thickness decreases from concrete pavement to concrete base to lean base. Therefore, the σ values, which were obtained from Ministry Report MI-76, represent larger coefficients of variation for lean concrete base than for concrete base, which are, in turn, larger than for concrete pavement.

As the specified thickness decreases, a given thickness deficiency becomes a greater percentage of the specified thickness. The equation for determining the payment amount is based upon the square of the ratio of the sample mean thickness to the specified thickness minus 5 mm. For example, for a thickness deficiency of 10 mm, and specified thicknesses of 300 mm and 150 mm, the payment factors are:

$$\text{for 300 mm} \rightarrow \text{payment} = \frac{(300 - 10)^2}{(300 - 5)^2} \times 100 = 96.6\%$$

$$\text{for 150 mm} \rightarrow \text{payment} = \frac{(150 - 10)^2}{(150 - 5)^2} \times 100 = 93.2\%$$

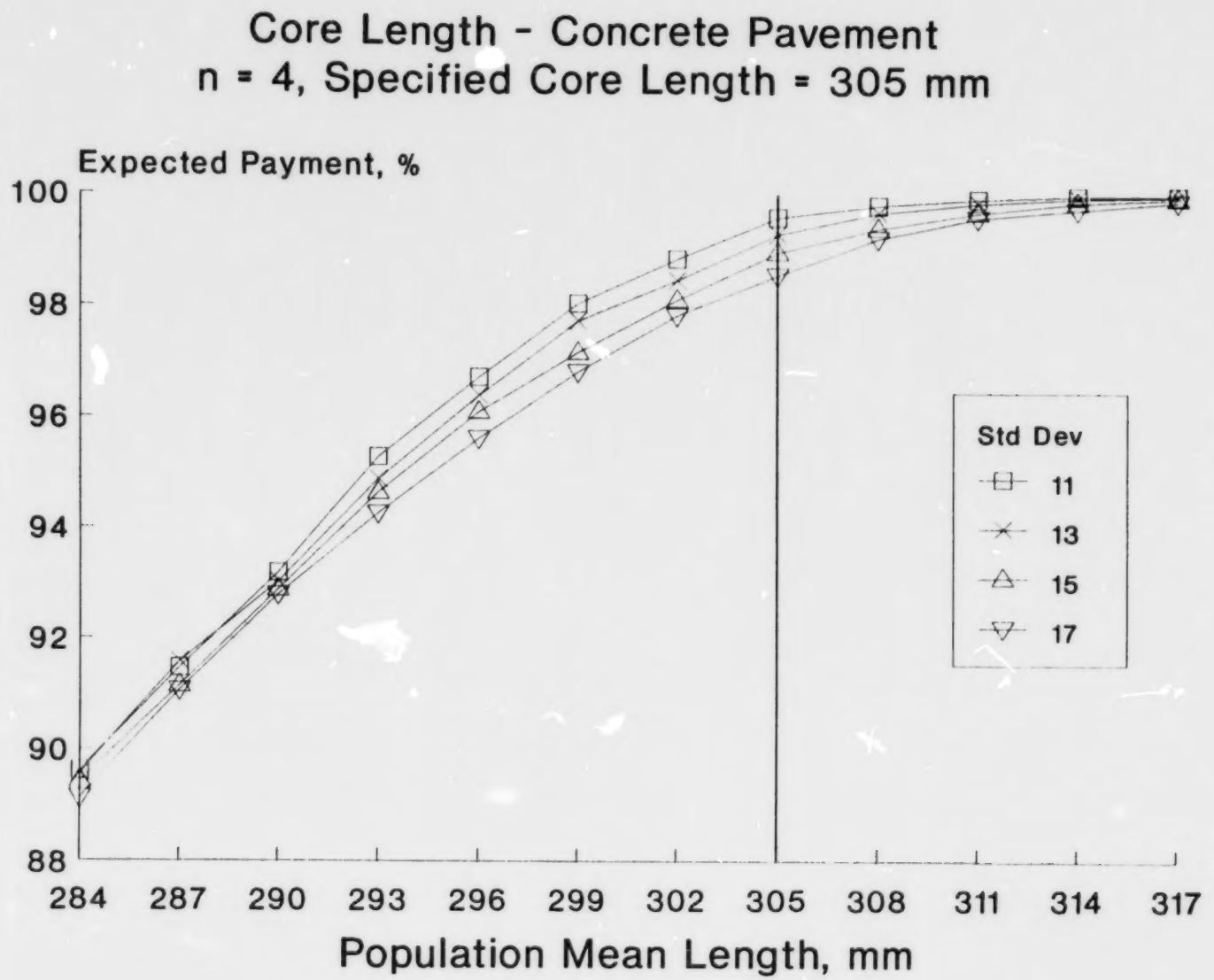


FIGURE 16. OPERATING CHARACTERISTICS FOR CORE LENGTH - CONCRETE PAVEMENT

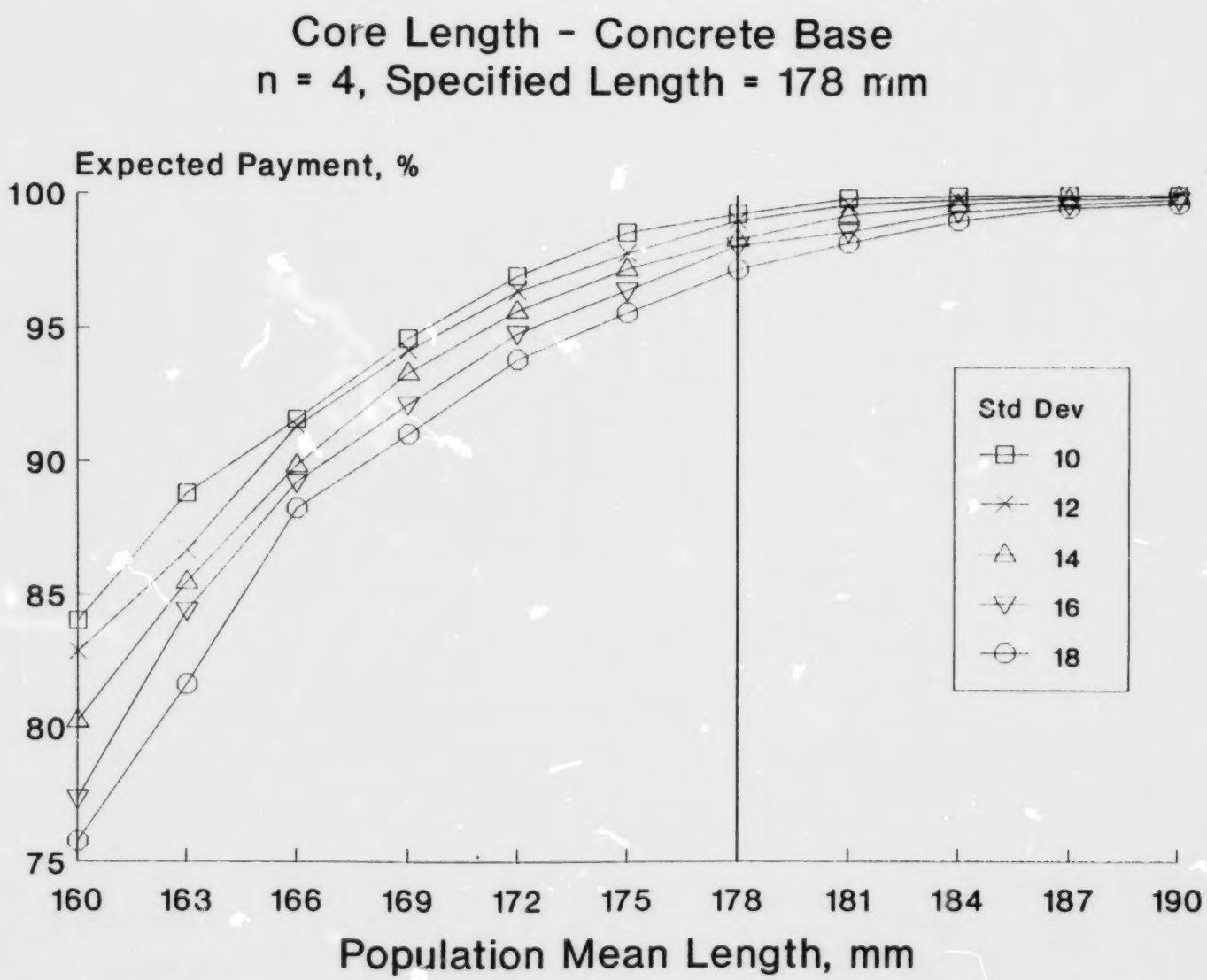


FIGURE 17. OPERATING CHARACTERISTICS FOR CORE LENGTH - CONCRETE BASE

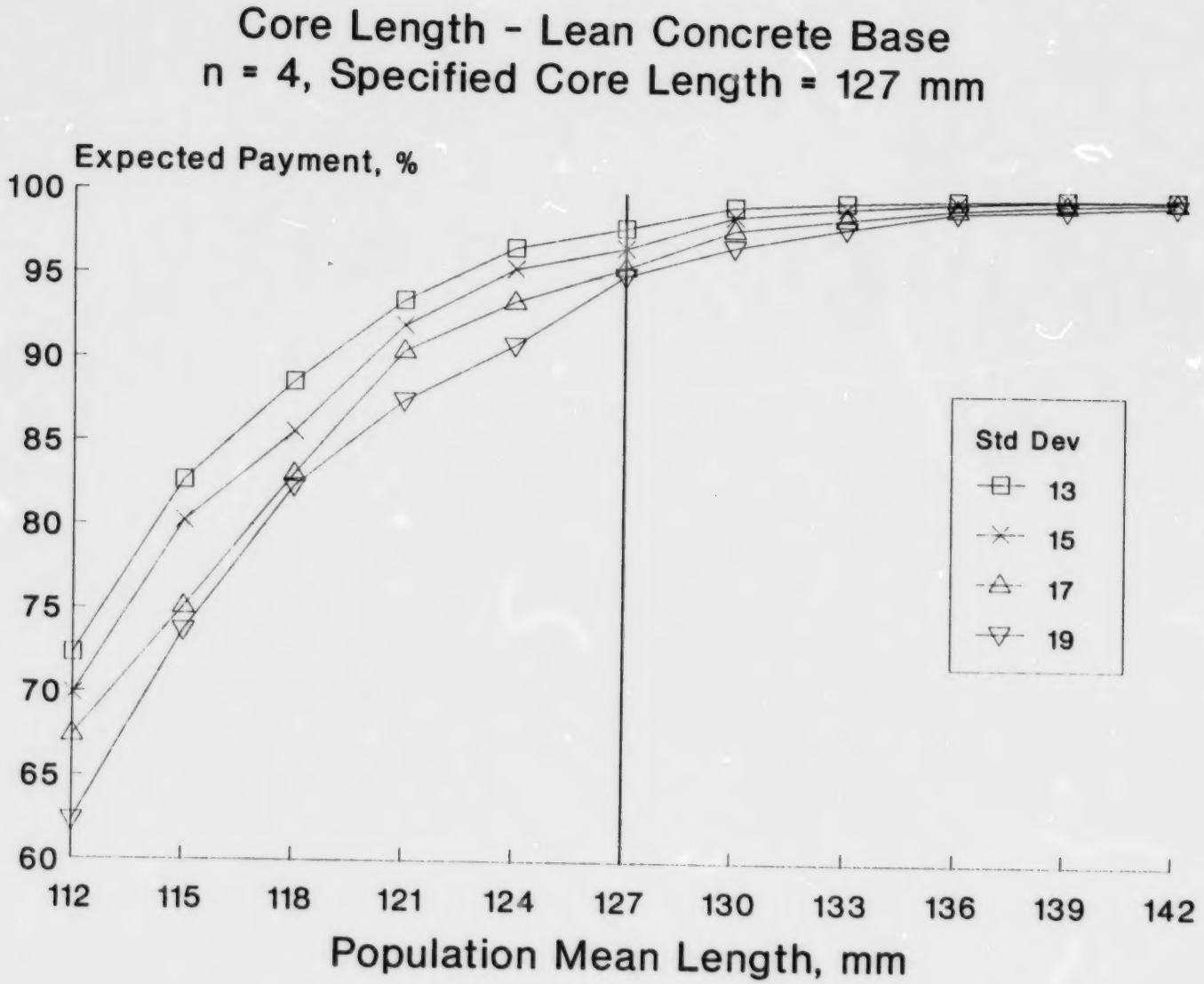


FIGURE 18. OPERATING CHARACTERISTICS FOR CORE LENGTH - LEAN CONCRETE BASE

The current payment determination procedures therefore penalize more severely for a given deficiency for smaller specified thicknesses. This may be appropriate in light of the fact that the given deficiency represents a greater percentage of the total thickness as the specified thickness decreases.

General Comments on the OC Curves

The acceptance procedures appear to work as planned by the Ministry. The expected payment values for the various core thicknesses are generally close to the payment adjustment values derived from the equation in the specifications.

For example, if the specified thickness is 305 mm, the payment determination equation indicates a payment of 97.4% for a core thickness of 296 mm (i.e., $[296/(305-5)]^2 \times 100$). Figure 16 indicates an expected payment, depending upon the σ value, of 95% to 97%. This bias toward a slightly lower payment is due to the fact that a sample that is estimated to have a thickness less than 296 mm will receive a payment of less than 97.4%, with the only minimum payment limit being 75% (at which time the slab is removed and replaced). However, the upper payment limit of 100% is reached when the thickness estimate is 300 mm (i.e., 305 - 5). This upper limit on payment always leads to some bias against the contractor for payment levels near 100%. This situation is discussed further in a paper by Weed (8).

Because the acceptance procedures are based on only sample means, the OC curves discriminate among different population standard deviations only around the specified acceptance limits. Unless the Ministry is willing to accept the assumption that the process standard deviation is constant from project to project and from supplier to supplier, consideration should be given to modifying the acceptance procedures to incorporate some control of variability. This could be accomplished by means of adding a Range limit or, preferably, by using PWL for acceptance decisions. There are numerous references available in the literature (2-10) that deal with the development and use of PWL acceptance procedures.

CHAPTER 4 - BITUMINOUS MATERIALS

INTRODUCTION

The information reviewed in the Bituminous Materials area was from a number of sources, including:

> "1986 Guide for Acceptance Procedure for Liquid Asphalts, Emulsified Asphalts and Emulsified Asphalt Primers," Engineering Materials Office, pp. 5-9.
>
> Special Provision - Bridge Deck Waterproofing, 1988.
>
> "Acceptance Requirements and Adjusted Payment Based on Asphalt Cement Content and Aggregate Gradation," Non-Standard Special Provision, Draft 1989-1, February, 1989.
>
> "Field Guide for the Acceptance of Bituminous Materials," Bituminous Section, Engineering Materials Office, Ontario Ministry of Transportation, February, 1989.

In addition, the following supporting document that was provided by the Ministry was reviewed for supplemental information regarding the development of the Bridge Deck Waterproofing Specification:

> "Development of a Statistically Based Acceptance Plan for Bridge Deck Waterproofing Membrane Thickness," Report EM-79, Ontario Ministry of Transportation and Communications, July, 1986.

GENERAL COMMENTS

The following comments relate to the review of the above documents relating to bituminous materials and mixes. The review considered only the statistical aspects of the acceptance procedures, and did not attempt to evaluate the appropriateness of the technical aspects and requirements, such as acceptance limits. The comments are presented individually, and, where appropriate, suggestions or recommendations are presented.

Liquid Asphalts, Emulsified Asphalts, etc.

1. On page 5 of the 1986 Guide, a re-test of a new sample is allowed in the event that the original tests on emulsified asphalt or emulsified asphalt primer fail. The procedure states that if re-testing is not commenced within 14 days of sampling, the original tests will govern. It is not clear whether this 14 day period is to commence at the time of the original sampling or to commence when the supplier is notified of the original failing test. In either event, it appears that the re-tests may not be conducted after 14 days even if the delay in testing is due to the Ministry and not to the supplier.

2. The development of the multipliers for determining adjustment points appears to be subjective and probably based on engineering judgement. Correspondence with Mr. D. F. Lynch indicates that a simulation of the payment approach was carried out on test results from Ministry contracts, and that the payment schedule was adjusted to be non-punitive to the supplier. This sounds like a reasonable approach. However, limits and price adjustments that appear to be arbitrarily established or which appear to be unrelated to performance are the most likely ones to be challenged, sometimes in court, by contractors and suppliers. Establishing correlations with performance is difficult for many tests, but an attempt should be made to do so whenever possible.

3. Adding the adjustment points for various tests to arrive at the total payment adjustment essentially assumes that the test results are independent or that the tests all measure different deficiencies. Adding the payment adjustments from different tests introduces the possibility that the supplier will be penalized twice for the same deficiency.

Care should be taken when establishing acceptance criteria to ensure that all of the acceptance tests (particularly ones which may have price adjustments) are necessary to evaluate the material and that the tests are not being stipulated just because they have always been done in the past.

If it is possible that some of the test results are correlated, or that the tests may measure the same deficiency, then it may be preferable to average the payment reductions rather than to add them together. Averaging does not directly consider the possible correlation, but it also does not implicitly assume that the tests are independent. The concept of adding the price reductions is not necessarily inappropriate, particularly when the tests are intended to measure totally different properties of the material.

4. The sampling and testing procedures do not appear to be based on multiple sampling and testing. This approach therefore assumes that variability is either constant or that it is not important, i.e., the material has a high degree of uniformity. The acceptance procedures allow for re-testing in the event the first test fails. The effect of re-testing is to increase the sample size from one to two. If variability were taken into account when setting the acceptance limits, then the limits should change for a sample size of two.

By giving the contractor the "benefit of the doubt" and using only the better test result, the acceptance procedure is implicitly doing one of the following: it is assuming that the poorer test result is somehow invalid (incorrect test procedure, damaged sample, etc.), or it is ignoring the concept of variability and assuming that a single test result can represent the quality of the total lot. Statistically, a better option would be to average the two test results unless there is some justification for believing that one of them is invalid (it is just as likely that the better test result is the invalid one as it is that the poorer result is invalid). Politically, the Ministry may believe that the current approach is preferable during the early implementation phase of the acceptance procedures.

Multiple sampling and testing should be considered as an option. This would allow both mean and variability to be controlled either by using both sample average and Range, or by

using PWL. Both of these techniques are employed in some of the other acceptance approaches reviewed in this report.

5. The current procedures call for collecting samples after a minimum of 4000 kg of material have been drawn from the tanker. As written, it is likely that the sample will be drawn right after the 4000 kg point. It would be preferable to use random sampling to select the point at which the sample is obtained. The initial 4000 kg could still be eliminated from the sample, and random numbers could be used to establish the sample point from the remainder of the tanker.

Bridge Deck Waterproofing

1. Membrane quality determination is based on single test results. However, correspondence with Mr. Lynch indicates that the single result that is reported is based on the average of 3 tests in some cases and 5 or 7 tests in other cases. It does not appear that the variability (range or standard deviation) of the test results is considered in the decision. The Ministry may wish to consider adding some control of variability, such as range or standard deviation, or preferably PWL. The acceptance procedures for membrane thickness are based on the concept of Percent Defective (100 - PWL). This would be something to consider for the case where multiple tests are conducted for membrane quality.

An extreme example will illustrate the potential problems that can arise for acceptance on mean alone. Two sets of three test results as shown below would have the same average:

Set 1 - 10 100 190 → $\bar{X} = 100$ $\sigma = 90$

Set 2 - 99 100 101 → $\bar{X} = 100$ $\sigma = 1$

Considering only the mean in the acceptance decision essentially assumes that the variability is constant from lot-to-lot and supplier-to-supplier.

2. The adjustment points for determining payment level for membrane quality were evidently established subjectively based upon engineering judgement. While this is sometimes the only option, it is better to attempt to relate the payment adjustment to the anticipated performance of the product. Typically, limits that are set by engineering judgement tend to be too tight due to the tendency to underestimate the inherent variability of the material and the process. This does not necessarily mean that this was the case with this specification, but it is a factor to consider whenever judgement is used to establish acceptance limits or payment adjustment levels.

3. The acceptance procedures for membrane thickness are based on multiple random sampling and the percent defective approach was used to develop the acceptance procedures. The development of this acceptance approach is outlined in Ministry Report EM-79. The procedures followed in this report appear to be appropriate. The percent defective approach incorporates both sample mean and sample standard deviation into the acceptance decision. The procedure is based on the sample standard deviation which is preferable to using the sample range. The payment factors were based on a continuous payment schedule to avoid large differences in payment for relatively small differences in percent defective.

However, some of the advantages of the above approach were lost when the procedure was simplified for field use. By developing a table of means and standard deviations to determine payment adjustment factors, rather than calculating the quality index, estimating percent defective and plugging this into the equation for the continuous payment schedule, the acceptance approach removes the benefits of the continuous payment schedule. Since the mean must be rounded to the nearest 0.1 and the standard deviation must be rounded to the nearest 0.05, the continuous percent defective approach is converted to a discrete approach.

Table 1 in the Special Provision has some relatively large steps in the payment reductions when going from one line to the next. The Ministry should consider modifying the acceptance

procedures to directly calculate the quality index. A table for converting the quality index to percent defective could be included in the Special Provision. The estimated percent defective could then be input into the continuous payment adjustment equation to determine the payment level. It may be preferable to use a PWL approach rather than percent defective. The two approaches achieve identical results, but the PWL terminology has a more positive image.

4. The Appendix in Report EM-79 presents a procedure for determining locations for obtaining membrane thickness measurements. The procedure uses random sampling concepts to identify the transverse sampling locations, but a systematic approach to determine the longitudinal location. This systematic approach of taking 10 equal intervals for the longitudinal location has the effect of eliminating the possibility that most of the bridge deck will be sampled. Some form of random sampling should be used to establish the longitudinal location of the samples as well as the transverse locations.

Asphalt Cement Content and Aggregate Gradation

1. The acceptance procedures appear to allow both Rotorex and Reflux extraction. These methods are likely to have different variabilities. Since acceptance limits should consider the process variability, the variability associated with the test procedure should be considered in establishing the acceptance limits. Even though ASTM procedures may allow the two methods to be used, using a single test method for establishing the acceptance limits and for making acceptance decisions is preferable since it eliminates some variability from the procedure. If the data that were used to establish the acceptance limits were obtained from both test procedures, then the limits are based on an "average" testing variability. More uniformity and repeatability could be obtained by specifying a particular test procedure.

2. The payment adjustment points were developed subjectively based on engineering judgement regarding the relative importance of the particular characteristic to the performance of the mixture. As noted previously, there is a tendency for limits and payment levels that are established by judgement to underestimate the effects of material and process variability, and thereby establish limits that are too restrictive.

Mr. Lynch indicated in his correspondence that historical data from actual projects were used to establish values for variability. One note of caution that must be considered whenever historical data are used is the fact that the historical data may not have been obtained under controlled conditions such as random sampling, etc. Historical data, therefore, sometimes tend to underestimate variability. There is no indication that this is the case for this specification, but it is a factor for the Ministry to consider.

3. It appears that up to 11 sieves may be included in determining the payment reduction for aggregate gradation. This seems like a rather large number in light of the fact that the price reductions are added for the various sieves to determine the total payment. It is possible that the results from sieve-to-sieve are correlated so that the same deficiency may receive price reductions more than once. It is noted that the price adjustment factors are much more severe for asphalt content and the 4.75 mm and 75 μm sieves than for the other sieves. It may be possible to base payment decisions on only asphalt content, and the 4.75 mm and 75 μm sieves, and to control the other sieve by requiring them to be part of the supplier's quality control procedures. Expected payment values are addressed further in the section on OC curves.

4. Table 3 (page 6) in the Non-Standard Special Provision includes allowable tolerances for the sample Range. These tolerances are independent of the number of samples. This may not be appropriate since it is likely that the sample Range will increase as the number of samples increases. This may lead to

more payment adjustments associated with sample Range for larger sample sizes.

5. Rather than having separate limits to control sample mean and sample range, and having separate payment adjustment factors for each, the Ministry should consider using the PWL approach which provides a single value on which to base acceptance decisions. This single value, PWL, combines both the sample mean and sample standard deviation (or range).

6. In the table of adjustment points for asphalt content and aggregate gradation, it is not clear how the adjustment for the 75 μm sieve is applied. If it means that the factor is 2.0 for the total deviation if the deviation is > 1.0%, then this creates a large anomaly in the payment factor determination. For example, for a 1.0% deviation, the adjustment is (1.0)(10) = 10%, while the adjustment for a deviation of 1.1% is (2.0)(11) = 22%. The application of this factor should be clarified.

7. The adjustment factors are evidently determined by engineering judgement. This approach is sometimes unavoidable. However, when there is only a subjective evaluation of the relationship between the test property and the expected performance of the pavement, there is a much greater chance that a contractor will challenge, possibly through the courts, the validity of the payment adjustment procedures.

8. The pay factors in Table 5 of the Non-Standard Special Provision can cause potentially inequitable payments. The discrete nature of the adjustments can lead to relatively large differences in payments for minor differences in adjustment points. While these situations will average out in the long run, they may create inequities for an individual contractor on a project. For example, from the table:

Adjustment Points	Percent Payment
23	64%
24	60%
25	55%

A continuous price adjustment plan, based on an equation or series of equations, would avoid this problem.

Field Guide for Acceptance of Bituminous Materials

1. Four sampling methods are described in the Guide. Since these methods almost certainly have different sampling variabilities, it is important to consider how the acceptance limits were developed. If the specification limits were derived from data based on one sampling location, and another is used for acceptance sampling, then the limits may not be appropriate for the new sampling location. While the risk of producing material that meets specification requirements is borne by the contractor under end-result specifications, the specifying agency should make an effort to eliminate as much variability as possible in the procedures for determining the acceptability of the materials. It would be preferable to stipulate a single sampling location than to continue to allow sampling at multiple locations.

2. The procedure in the Guide (pages 1-14 to 1-17) for identifying the limits of rejectable material appears to be based on the concept that a single sample can represent the quality of the material. This fails to consider the variability of the material. The fact that a core gives an acceptable result at one location and an unacceptable result some distance further does not imply that the material necessarily goes from "good" to "bad" somewhere between the two core locations. In his correspondence, Mr. Lynch indicates that the current system is working well and the industry is satisfied with the status quo. He also indicates that the Ministry is moving to an end-result system with both mean and Range considered on a lot basis. This is certainly preferable to the procedure outlined in the Guide.

3. The visual acceptance for segregation (Guide pages 1-17 and 1-18) seems highly subjective and very dependent upon the opinion of the inspector or engineer. This type of characteristic is difficult to measure and does not lend itself to end result applications. A characteristic such as segregation is usually addressed as an inspection item rather than a measurable end-result item with price adjustments. However, the basis on which the price adjustments were derived, based on Mr. Lynch's correspondence, seem logical and defensible. The biggest potential problem with such an approach is the very subjective nature of the decision and the potential for different inspectors to make different decisions on the same pavement.

4. The procedure for establishing sampling locations for bridge deck waterproofing membrane thickness in the Guide are preferable to that shown in Report EM-79. The approach of using stratified random sampling is preferable to using systematic sampling.

5. On page 3-9 of the Guide, the adjustment points for Cone Penetration @ 50°C for waterproofing material can lead to a large anomaly in the determination of adjustment points. This case is similar to that mentioned above for the adjustment points for gradation for the 75 μm sieve. For example, for a cone penetration test result of 200, the adjustment points are (200 - 160)(0.1) = 4.0, while the adjustment points for a test result of 201 are (201 - 160)(0.2) = 8.2. This is a large difference in adjustment points for a very small difference in the test result.

6. Multiplying the thickness and quality payment adjustment factors for bridge deck waterproofing essentially assumes that the two are independent. While this seems like a reasonable assumption, it might be possible that some quality characteristic might affect the ease of application in the field. Possible correlation of test results should always be ruled out before deciding to make price adjustments additive or multiplicative.

OC CURVES

OC curves were developed for **Bridge Deck Waterproofing Membrane Thickness** and for **Asphalt Cement Content and Aggregate Gradation.** In each simulation, 1000 lots were simulated with various population means and standard deviations (σ), and payment levels were determined in accordance with the appropriate acceptance requirements. The σ values used in the simulations were based on data from Ministry Report EM-79 and from the Public Roads (1) articles discussed previously. It was assumed that each of the properties could be satisfactorily represented by the normal distribution.

Bridge Deck Waterproofing Membrane Thickness

Figure 19 presents the OC curves for bridge deck waterproofing membrane thickness. Since the acceptance procedures call for the engineer to decide upon the course of action when the lot mean thickness exceeds the upper limit of 6.0 mm in the table in the Special Provision (page D-4), some assumption had to be made when conducting the simulation. Two sets of curves are therefore shown in Figure 19.

Figure 19(a) is based on the assumption that all lots with mean thickness in excess of 6.0 mm will receive full (100%) payment. Figure 19(b) is based on the assumption that all lots with mean thickness in excess of 6.0 mm will require removal and replacement (i.e., 0% payment). It is likely that the real situation will be between these two extreme limits. The two figures are identical except for population means near the upper limit (i.e., 5.0, 5.5 and 6.0). These populations produce sample means that are sensitive to the assumptions regarding payment for means in excess of 6.0 mm.

Ministry Report EM-79 indicates (on page 13) that the objective of the acceptance procedures is to have the membrane on the deck between 5.0 mm and 6.0 mm. thick. Figure 19 indicates that populations with mean thickness at the lower limit of this range, i.e., 5.0 mm, have a fairly low expected payment except for the smallest σ values simulated. This is particularly true for

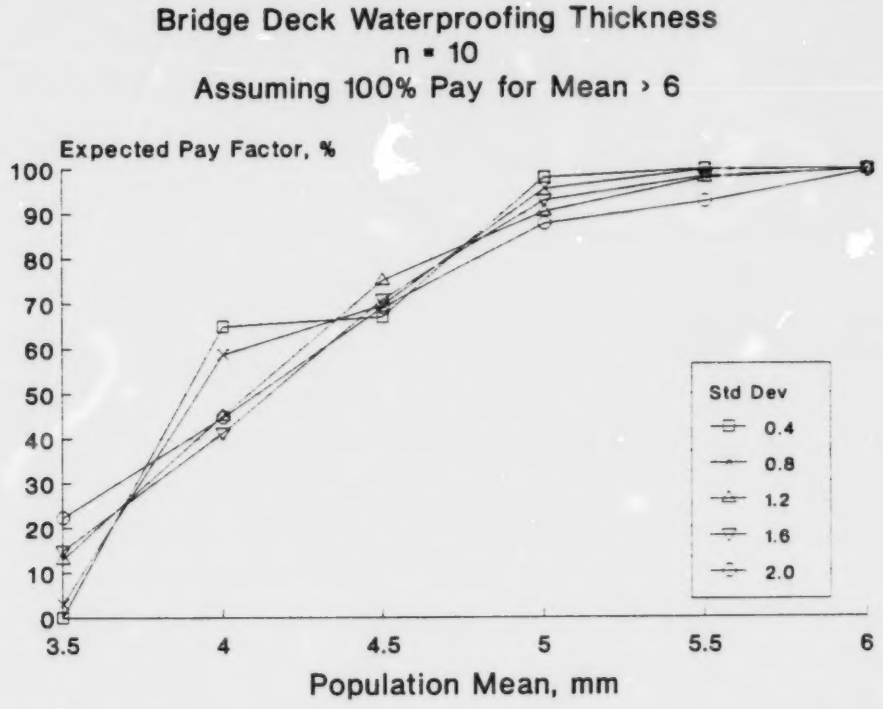


FIGURE 19(a). OPERATING CHARACTERISTICS FOR BRIDGE DECK WATERPROOFING MEMBRANE THICKNESS - ASSUMING 100% PAYMENT FOR MEAN THICKNESS > 6.0 mm

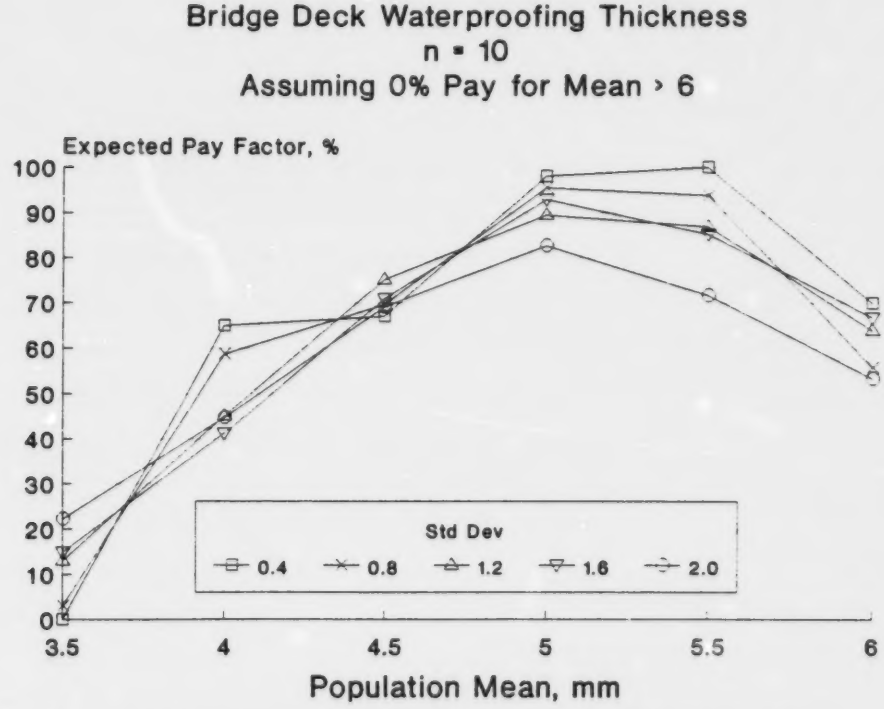


FIGURE 19(b). OPERATING CHARACTERISTICS FOR BRIDGE DECK WATERPROOFING MEMBRANE THICKNESS - ASSUMING 0% PAYMENT FOR MEAN THICKNESS > 6 mm

the case where zero payment is assumed for sample means greater than 6.0 mm.

Asphalt Cement Content and Aggregate Gradation

Computer simulation was used to develop separate OC curves for asphalt cement content and for percent passing for each of the 11 sieves shown in Table 1 (page 4) of the Non-Standard Special Provision - Hot Mix ERS. Since the acceptance procedures stipulated an allowable ± tolerance from the Job Mix Formula (JMF), and since a symmetrical normal distribution was used in the simulation, the OC curves for expected payment are also symmetrical about the JMF target value. The OC curves are plotted for population means from the center of the tolerance range to the maximum allowable tolerance limit.

Asphalt Cement Content. The OC curves for asphalt cement content are presented in Figure 20. The expected payment curves for population means show essentially no price reductions except for the largest σ value simulated. The largest σ value is probably large enough to have price adjustments associated with exceeding the allowable range tolerance. The expected payment drops off as the population means approach and exceed the upper and lower tolerance limits.

19 mm, 16 mm, 13.2 mm and 9.5 mm Sieves. OC curves for percent passing for various σ values for the 19 mm, 16 mm, 13.2 mm and 9.5 mm sieves are presented in Figure 21. The sieves can be presented with the same OC curves since the tolerance range, ± 5 percent passing, and the adjustment point factors, i.e, 0.1 for mean and 0.2 for range (Table 5 in Non-Standard Special Provision), are the same for each of the sieves. The expected payment values are quite high for most of the σ values simulated. However, it must be remembered that four different sieves have this OC curve and that the payment adjustment factors are additive.

4.75 mm Sieve. OC curves for the percent passing the 4.75 mm sieve are shown in Figure 22. Since the adjustment point factor for mean for this sieve is five times greater than for the

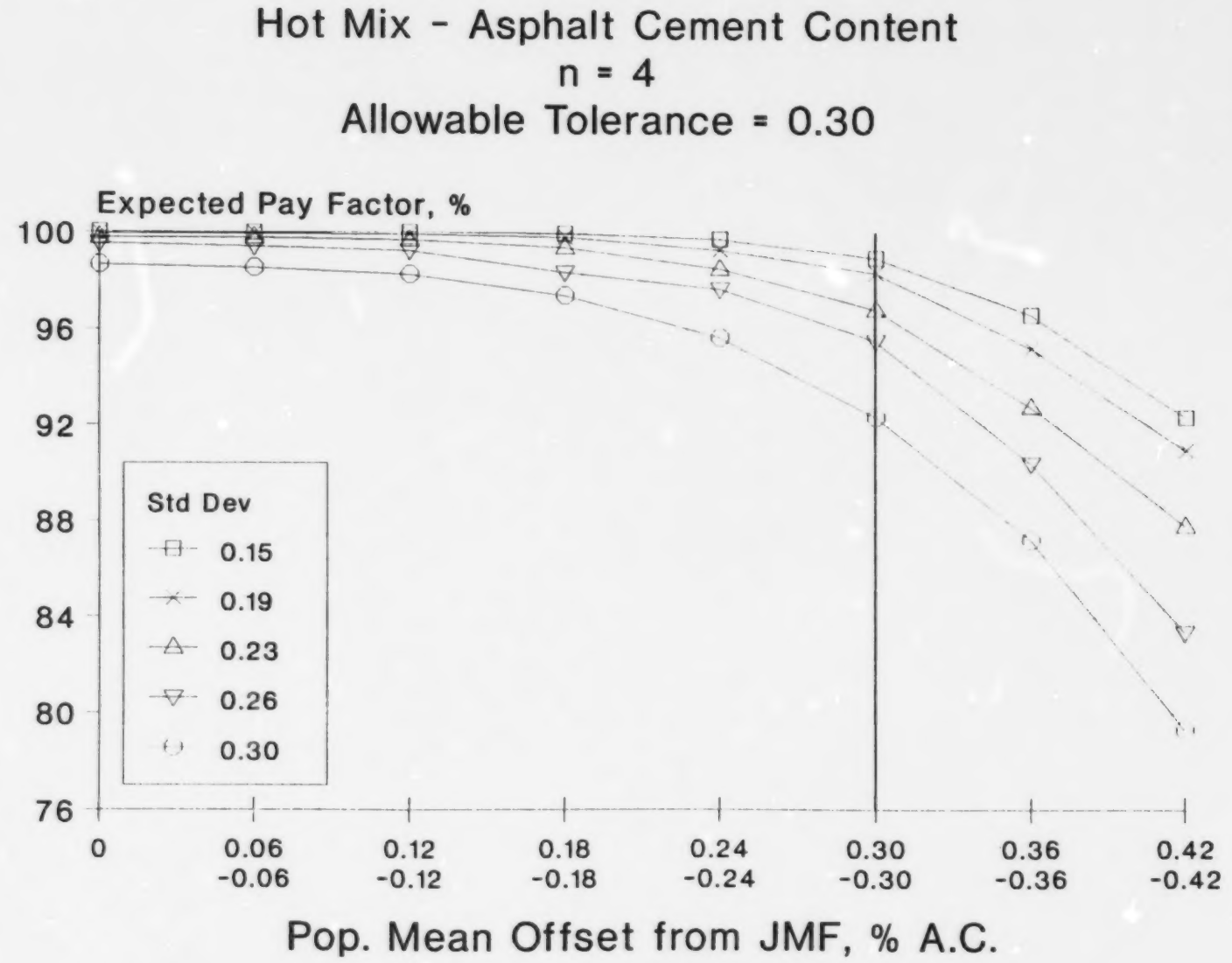


FIGURE 20. OPERATING CHARACTERISTICS FOR HOT MIX - ASPHALT CEMENT CONTENT, n = 4

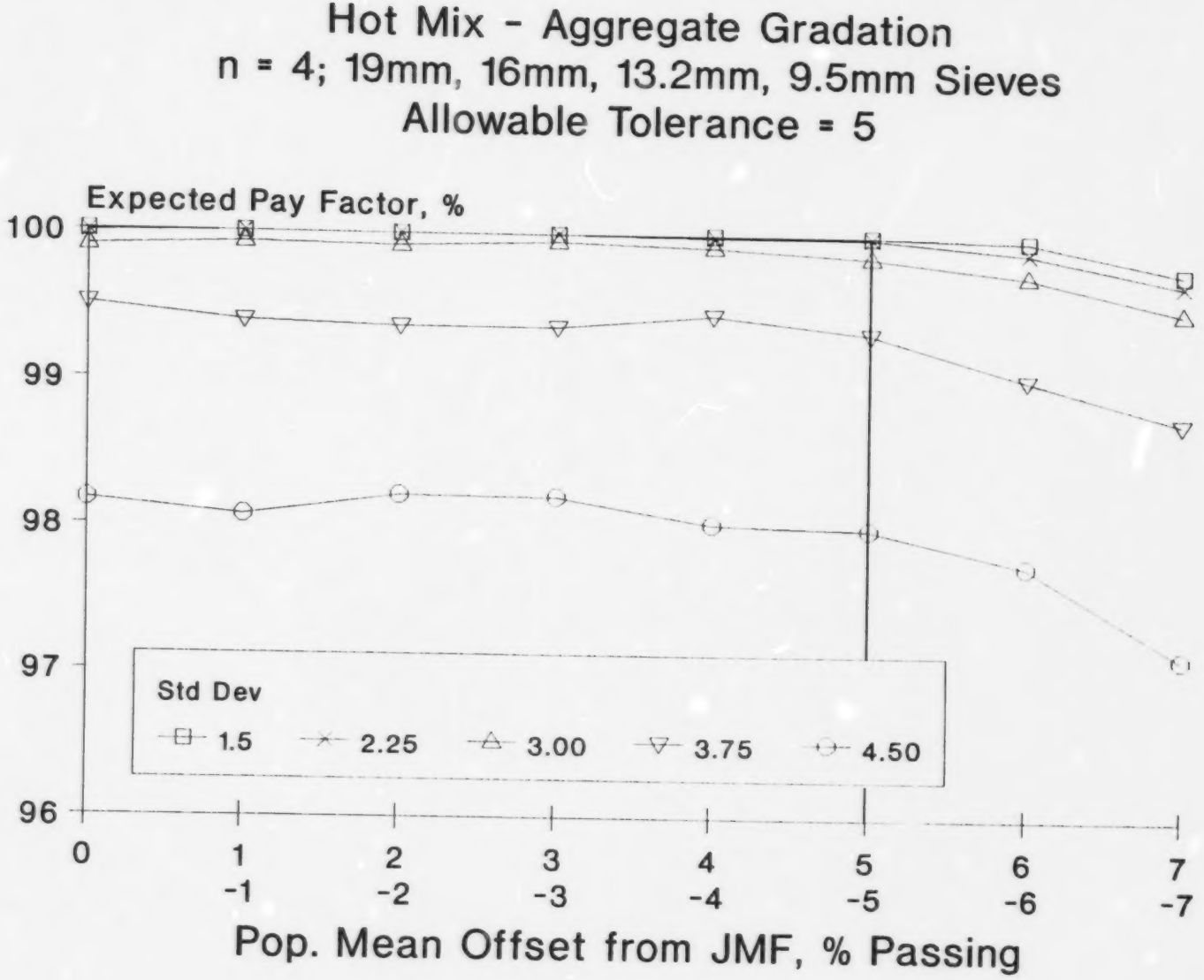


FIGURE 21. OPERATING CHARACTERISTICS FOR HOT MIX - GRADATION FOR 19 mm, 16 mm, 13.2 mm AND 9.5 mm SIEVES, n = 4

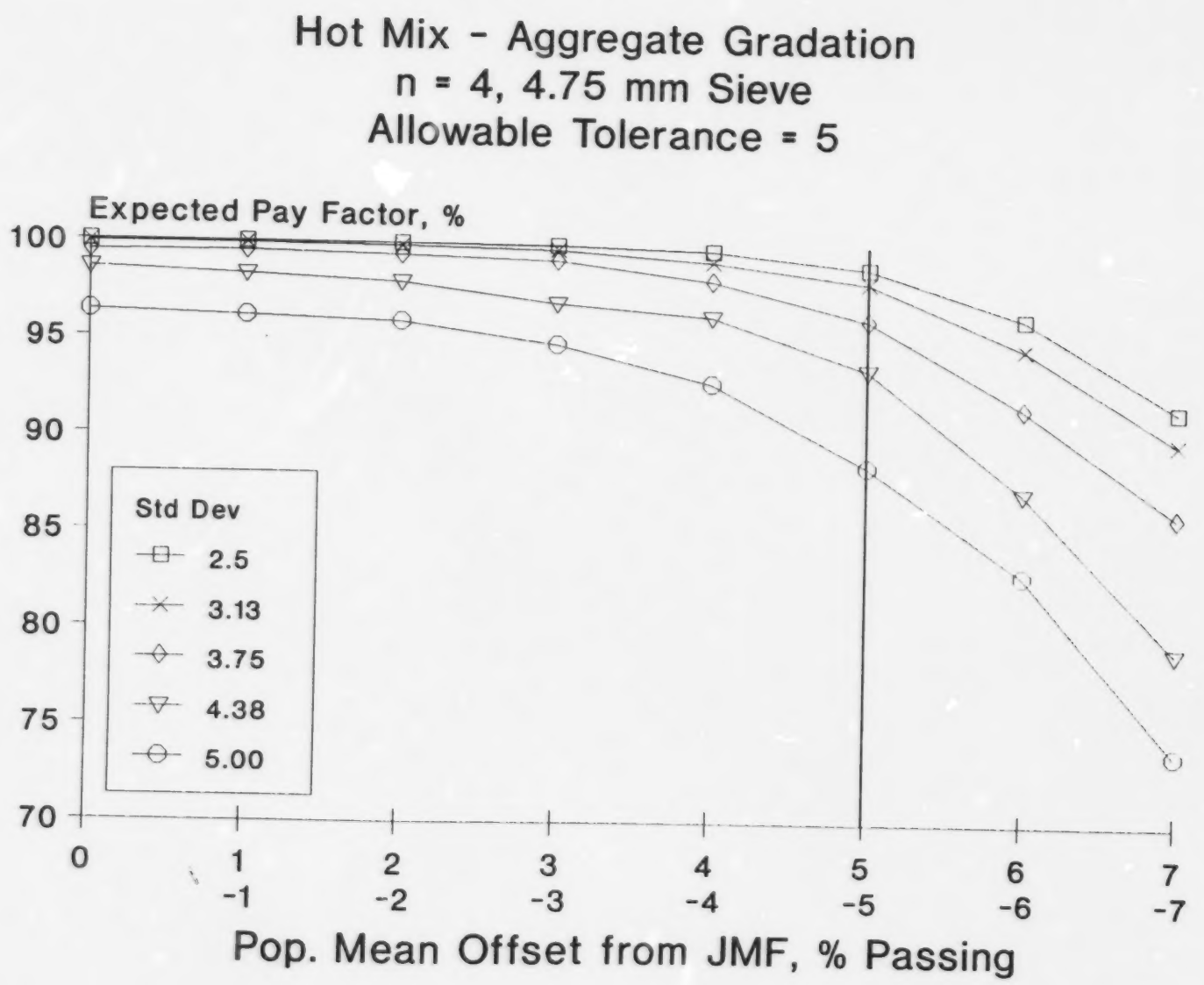


FIGURE 22. OPERATING CHARACTERISTICS FOR HOT MIX - GRADATION FOR 4.75 mm SIEVE, n = 4

previous sieves, the expected payment values for this sieve are considerably lower. The largest σ value simulated has an expected price reduction of approximately 4 percent even for population means centered on the JMF. This is due to exceeding the allowable range tolerance. Because of the large adjustment points factor, the expected payment drops rapidly as the population means approach and exceed the tolerance limits.

2.36 mm Sieve. OC curves for percent passing the 2.36 mm sieve are presented in Figure 23. The curves are similar to those for the larger sieve sizes which have the same adjustment point factor, i.e., 0.1 for mean and 0.2 for range.

1.18 mm Sieve. OC curves for percent passing the 1.18 mm sieve are presented in Figure 24. Once again, the curves are similar to those for the larger sieve sizes which have the same adjustment point factor.

600 μm Sieve. OC curves for percent passing the 600 μm sieve are presented in Figure 25. The expected payment is slightly less for population means outside the tolerance limits than for some of the other sieves because the adjustment points factor for this sieve is 0.2 for mean as opposed to 0.1 for most of the larger sieves.

300 μm Sieve. The OC curves for percent passing the 300 μm sieve shown in Figure 26 have higher expected payment values than the other sieves. This is because the typical σ values that were simulated for this sieve are smaller than those for the other sieves, and the tolerance limits are not considerably smaller than for the other sieves.

150 μm Sieve. OC curves for percent passing for the 150 μm sieve are presented in Figure 27. The curves exhibit the same general shape as for the other sieves. The expected payment values are large because the typical σ values simulated are relatively small in comparison with the tolerance limits for mean and range.

75 μm Sieve. OC curves for percent passing for the 75 μm sieve are presented in Figure 28. The expected payments are essentially 100 percent for population means within the allowable

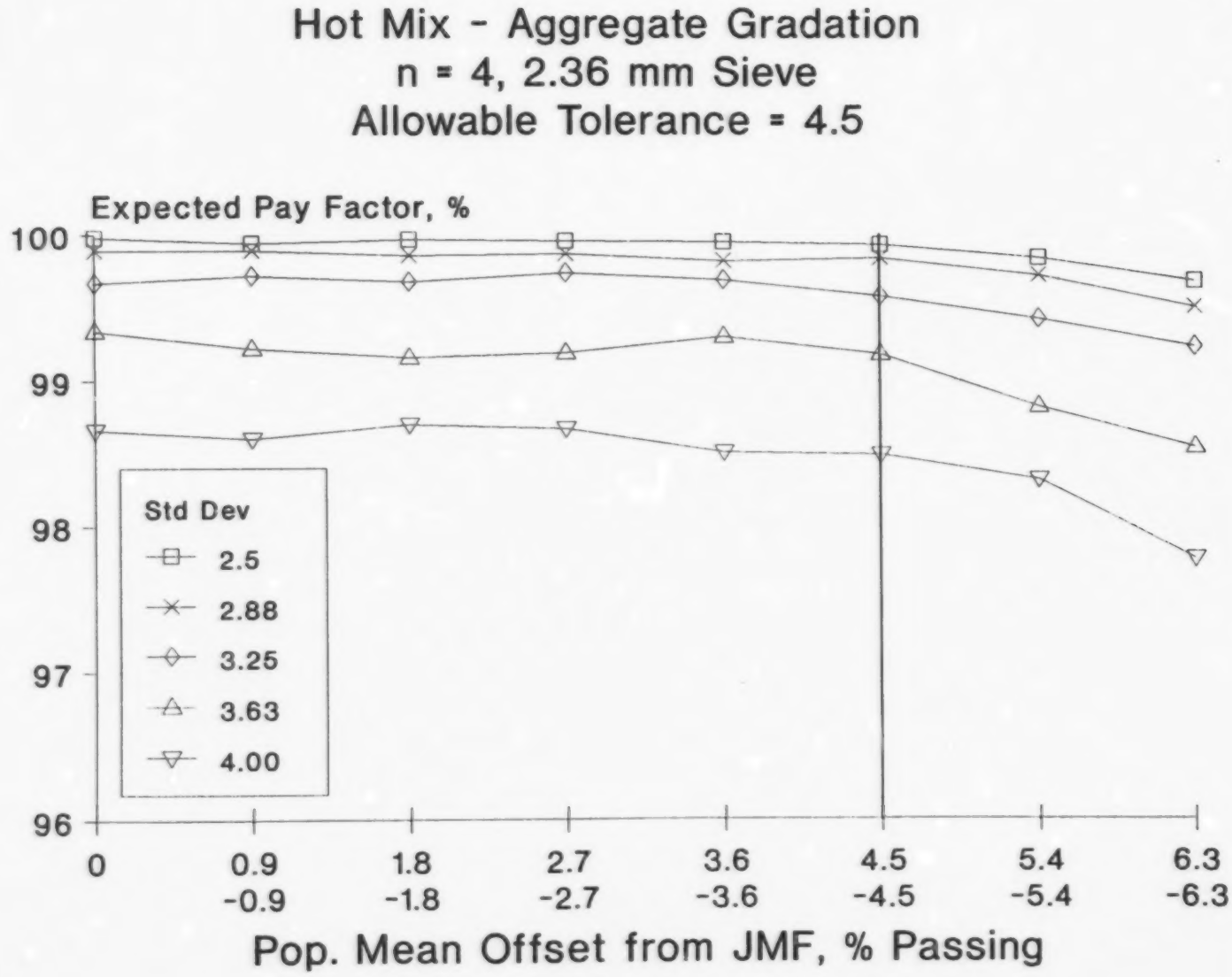


FIGURE 23. OPERATING CHARACTERISTICS FOR HOT MIX - GRADATION FOR 2.36 mm SIEVE, n = 4

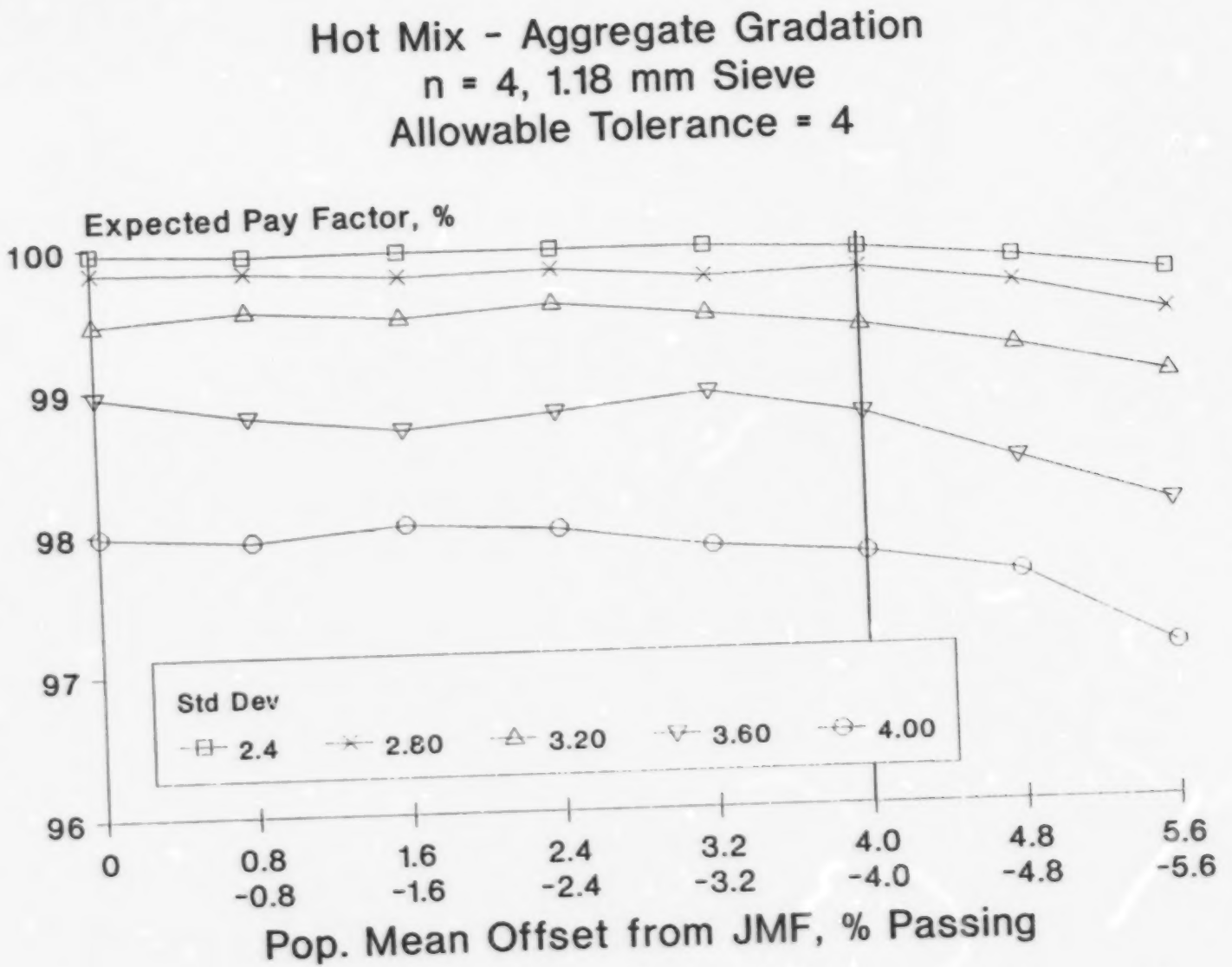


FIGURE 24. OPERATING CHARACTERISTICS FOR HOT MIX - GRADATION FOR 1.18 mm SIEVE, n = 4

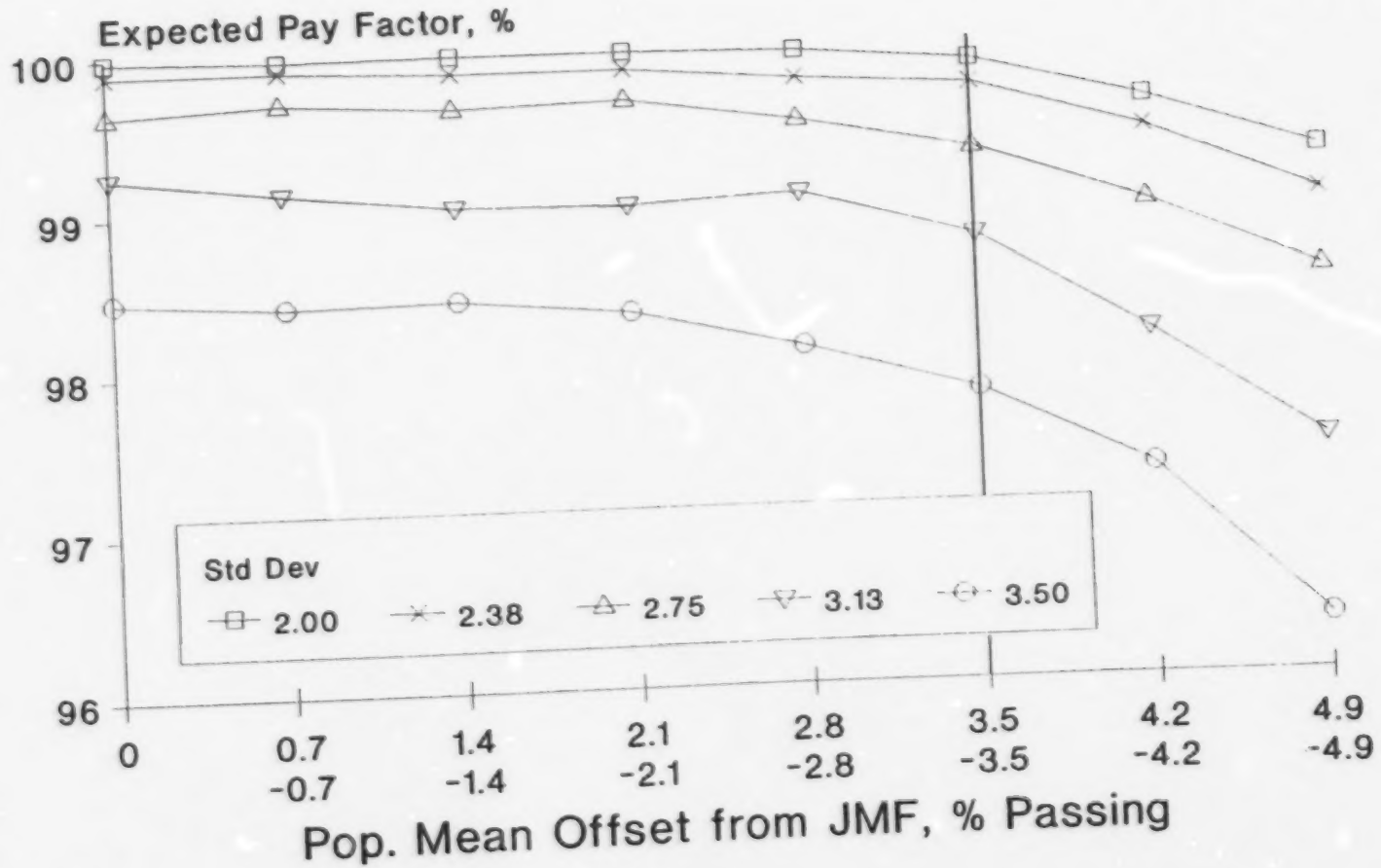


FIGURE 25. OPERATING CHARACTERISTICS FOR HOT MIX - GRADATION FOR 600 μm SIEVE, n = 4

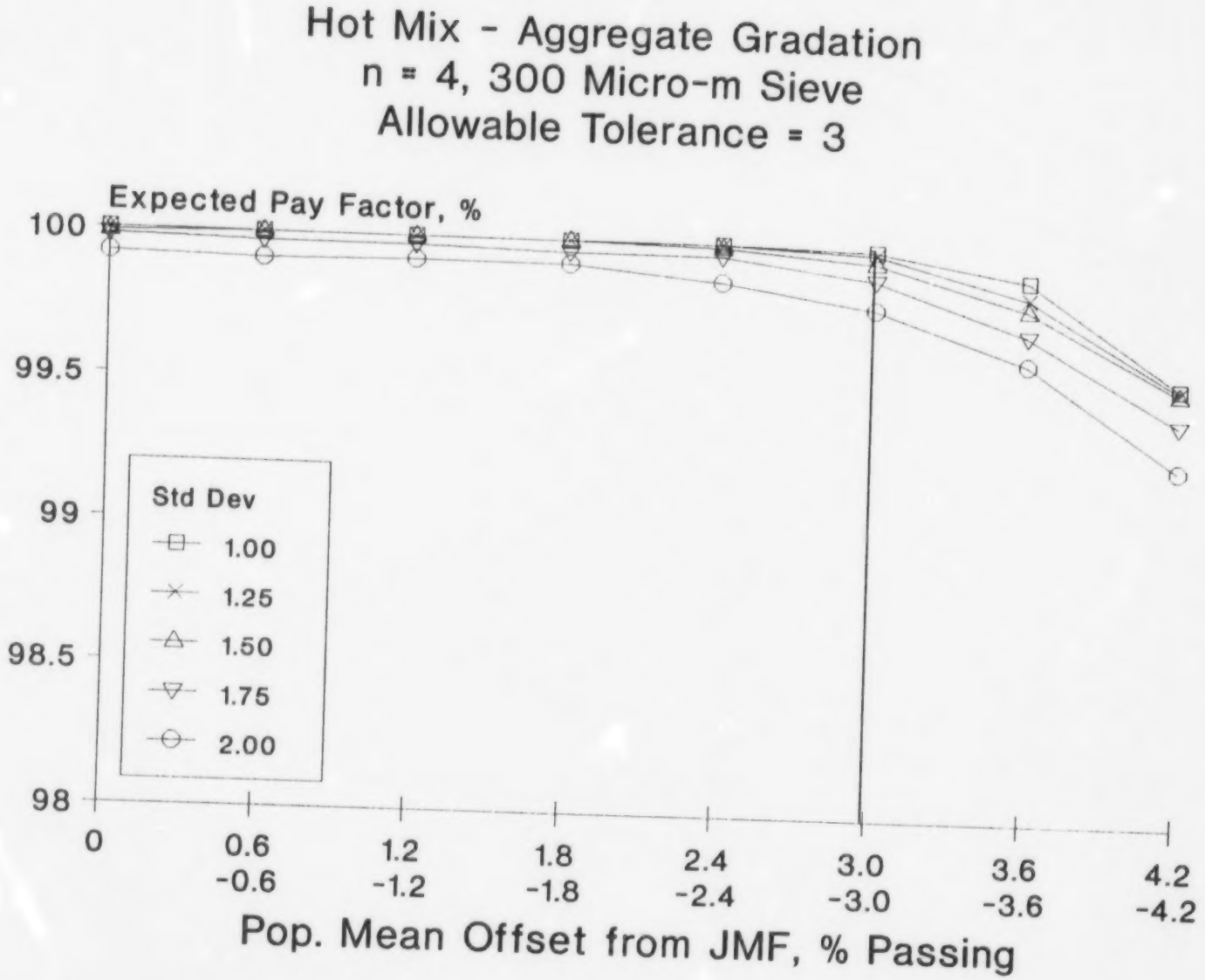


FIGURE 26. OPERATING CHARACTERISTICS FOR HOT MIX - GRADATION FOR 300 μm SIEVE, n = 4

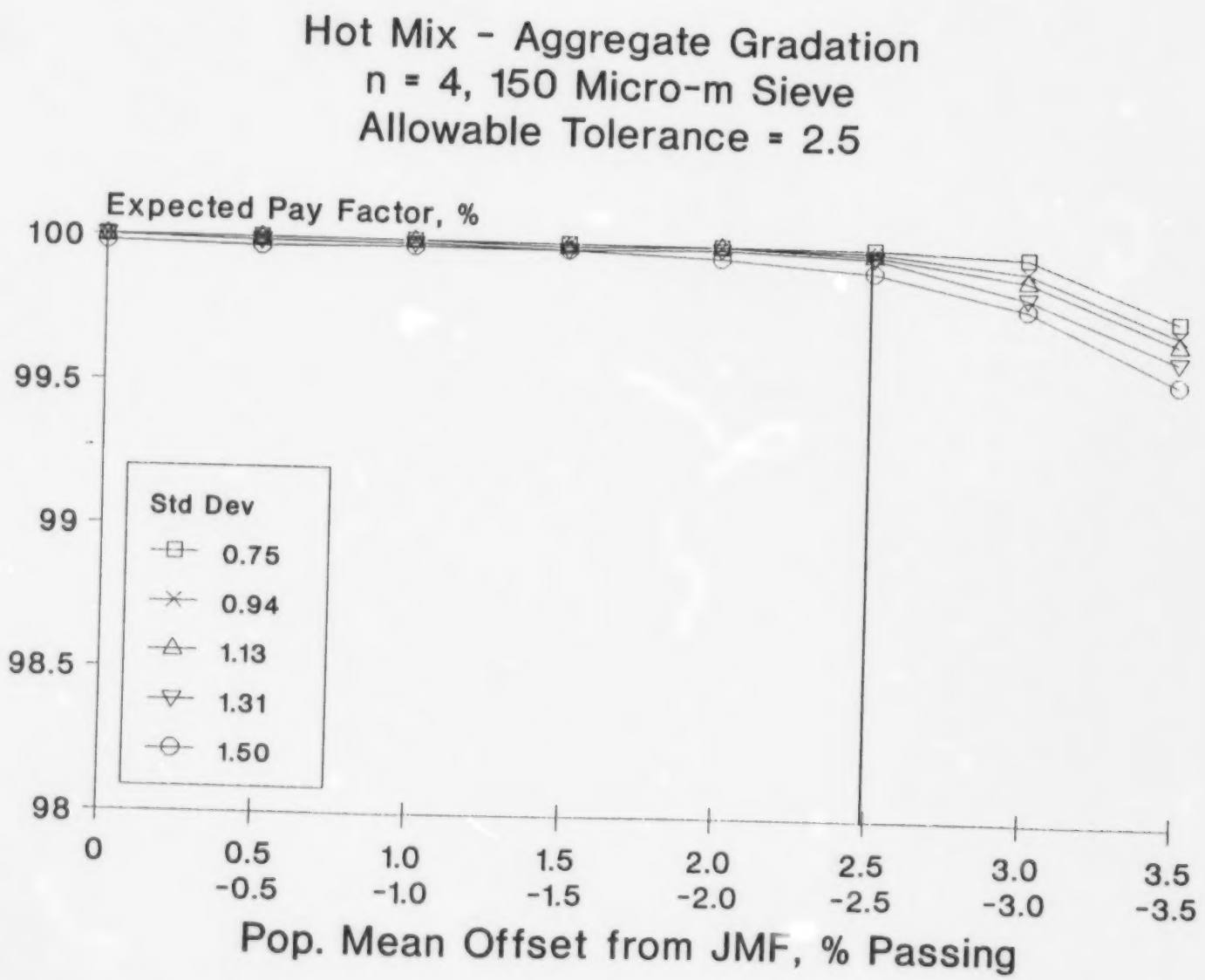


FIGURE 27. OPERATING CHARACTERISTICS FOR HOT MIX - GRADATION FOR 150 μm SIEVE, n = 4

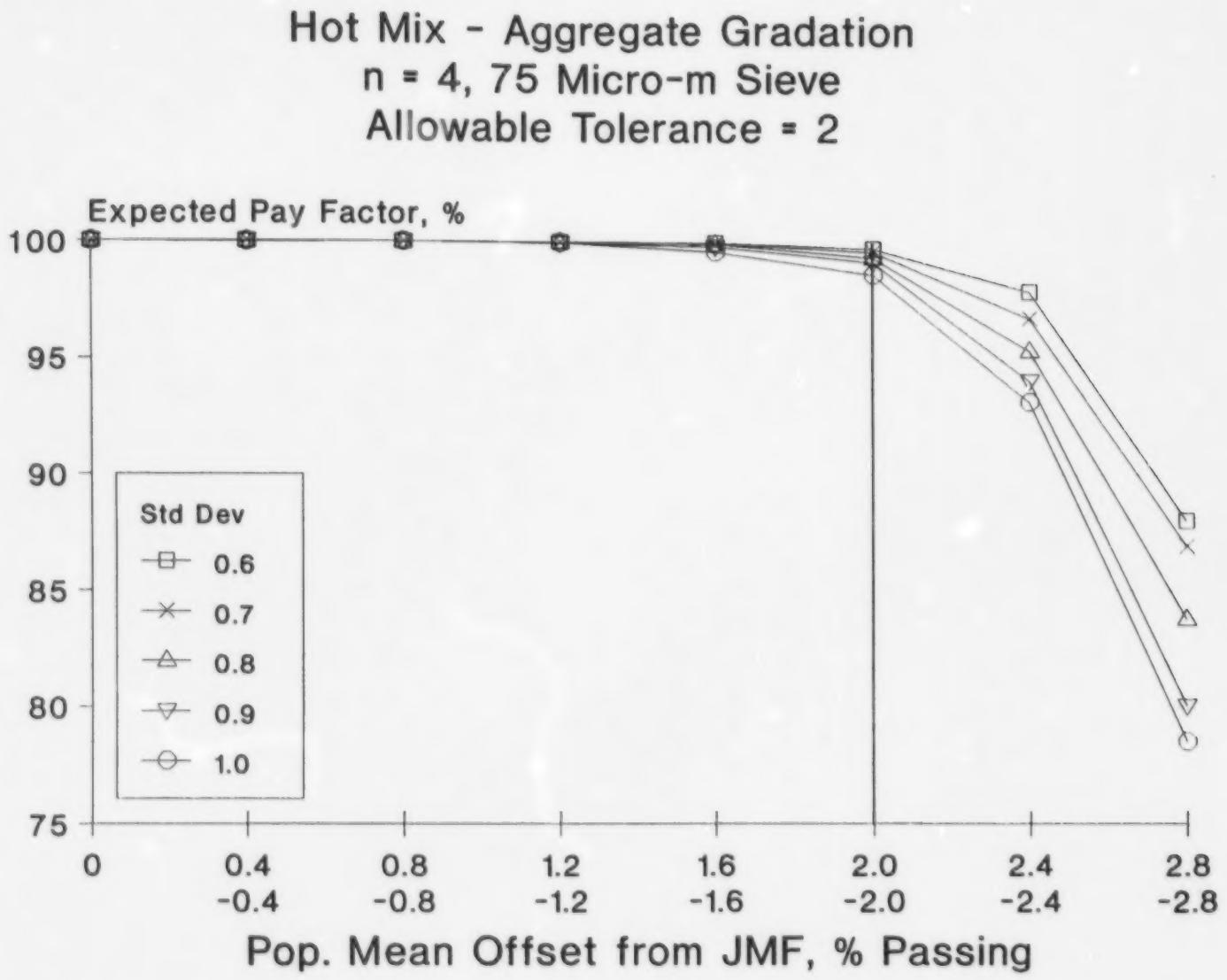


FIGURE 28. OPERATING CHARACTERISTICS FOR HOT MIX - GRADATION FOR 75 μm SIEVE, n = 4

tolerances. This is because the typical σ values simulated are small in comparison with the allowable mean and range tolerances. However, the expected payment values fall rapidly as the population means exceed the tolerance limits. This is because the adjustment points factor, 1.0 or 2.0, for this sieve is up to 10 to 20 times greater than for the other sieves.

Effect of Number of Sublots

Table 1 on page 4 of the Non-Standard Special Provision - Hot Mix ERS provides tolerance limits for sample mean for sample sizes (number of sublots) ranging from 4 to 14. The tolerance limits are tightened as the sample size increases to reflect the increasingly smaller variance for the distribution of sample means. However, the tolerance limits (page 6 of Hot Mix ERS) for sample range are independent of the number of sublots. It is likely that the sample range will increase as the sample size increases.

To consider the effect of increasing the number of samples without increasing the range tolerance limits, a series of simulations for asphalt cement content and aggregate gradation was conducted using 10 sublots per lot. The OC curves for these simulations are presented in Figures 29 through 37. These plots can be compared with the corresponding plots for 4 sublots per lot that are presented in Figures 20 through 28.

A comparison of the OC curves for 4 sublots with those for 10 sublots for asphalt cement content and for each sieve shows that the expected payments are always lower for 10 sublots. This reduction could be attributable to the narrower tolerance limits on the mean. However, because the expected payments are essentially constant for means within the allowable tolerances, it is likely that all of the additional payment reduction is due to the fact that the range tolerance was not changed as the number of sublots increased.

The Ministry should consider developing wider limits to accommodate the larger numbers of sublots. **A better alternative would be to switch to the use of PWL for acceptance decisions.**

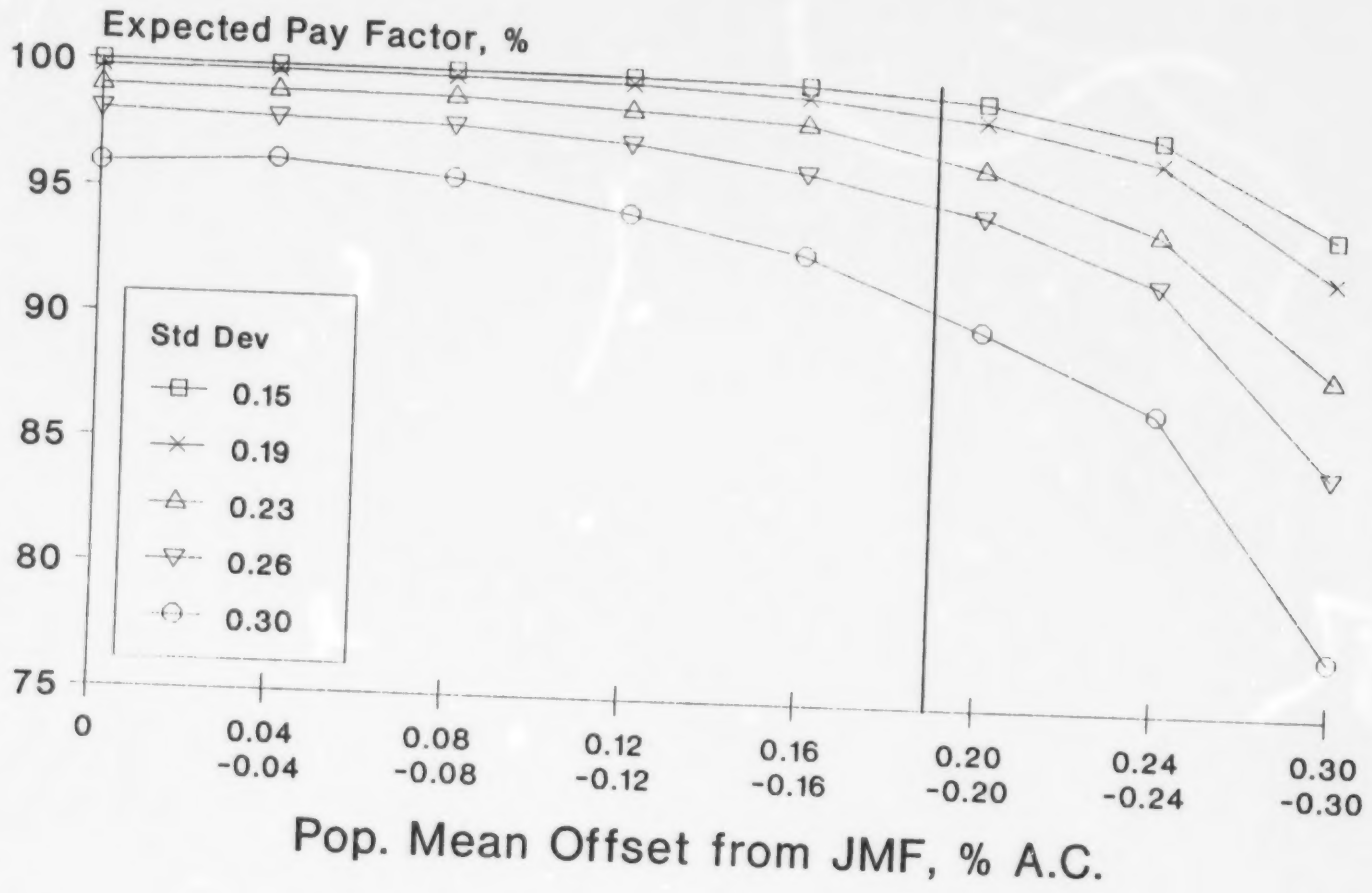


FIGURE 29. OPERATING CHARACTERISTICS FOR HOT MIX - ASPHALT CEMENT CONTENT, n = 10

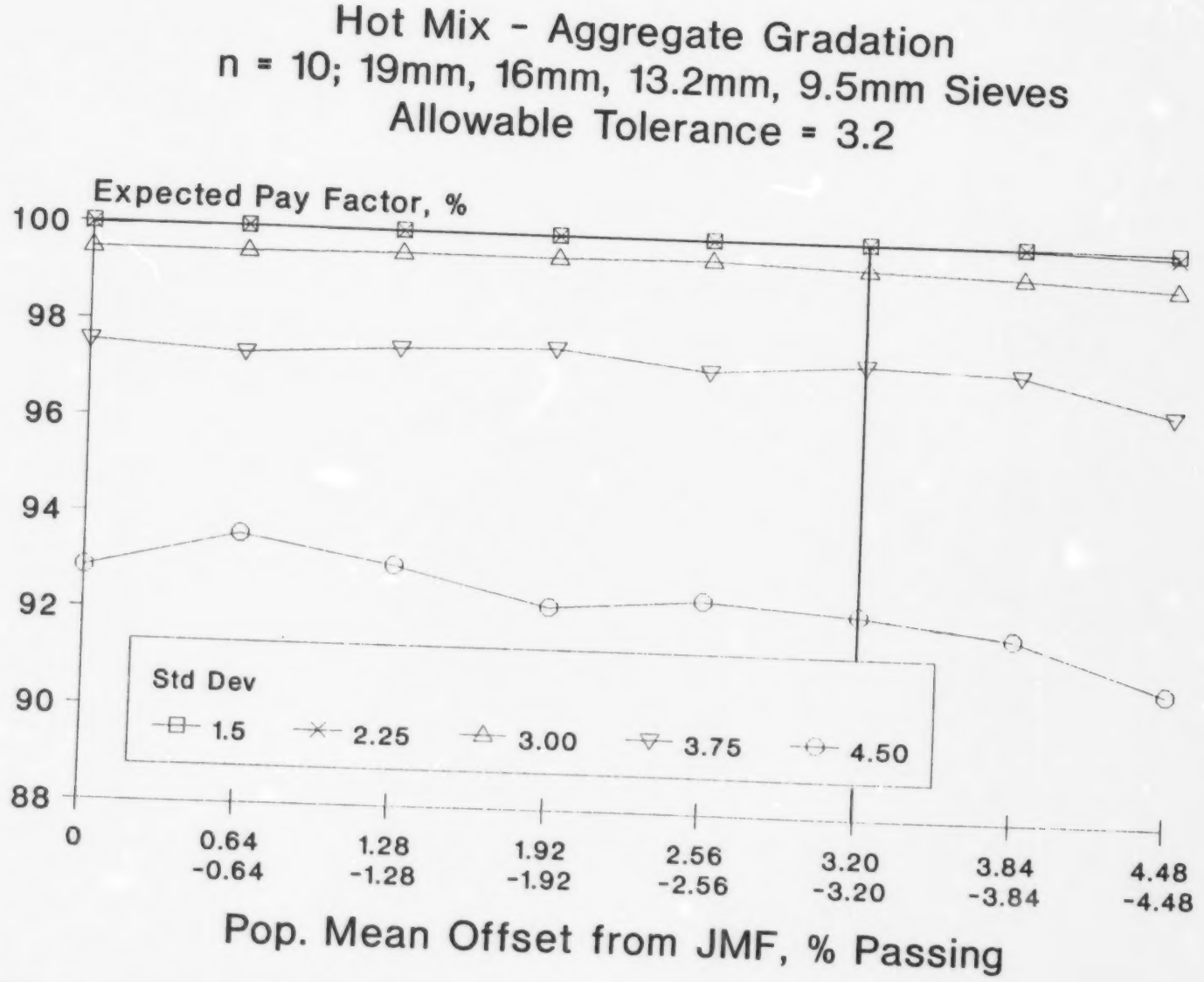


FIGURE 30. OPERATING CHARACTERISTICS FOR HOT MIX - GRADATION FOR 19 mm, 16 mm, 13.2 mm AND 9.5 mm SIEVES, n = 10

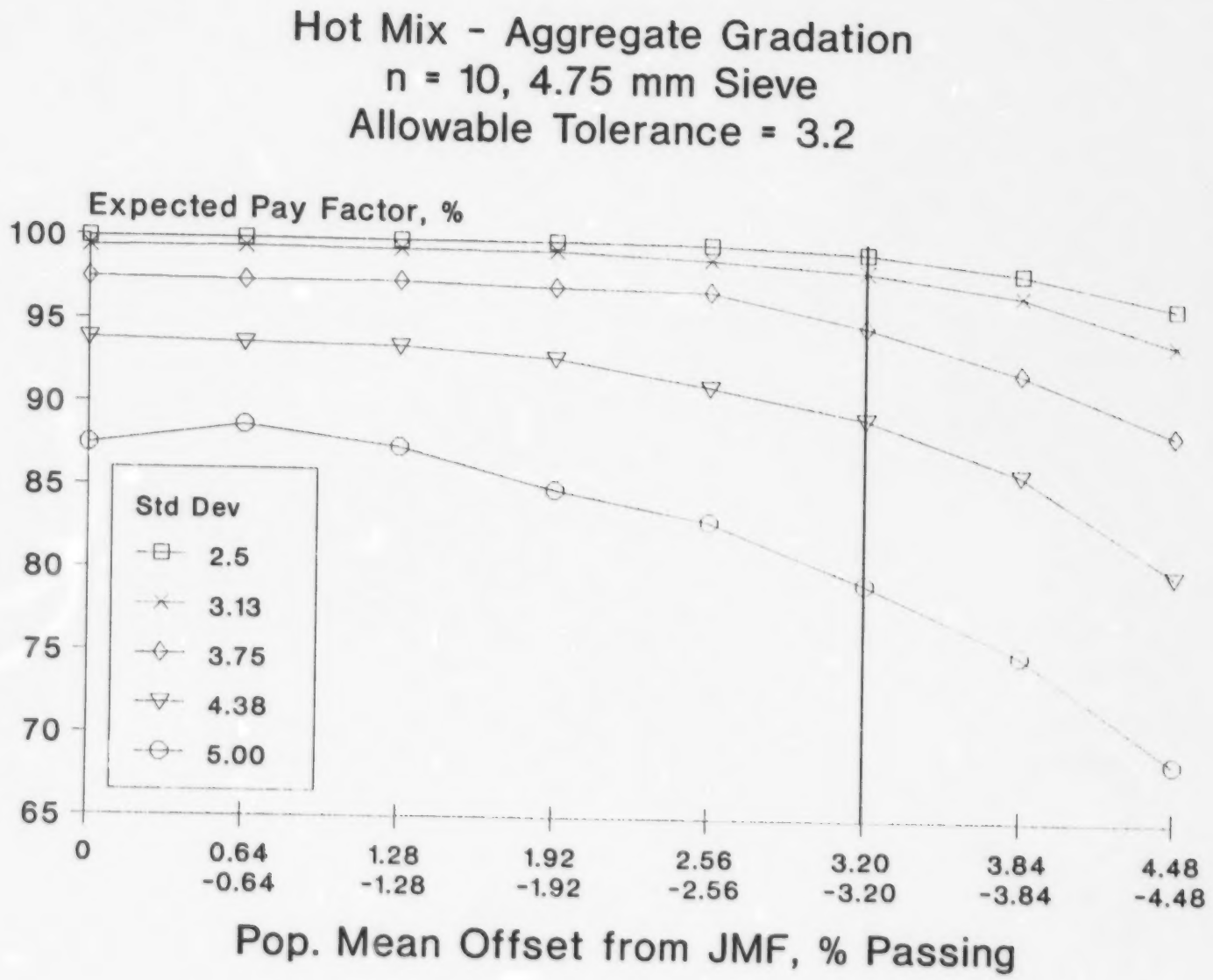


FIGURE 31. OPERATING CHARACTERISTICS FOR HOT MIX - GRADATION FOR 4.75 mm SIEVE, n = 10

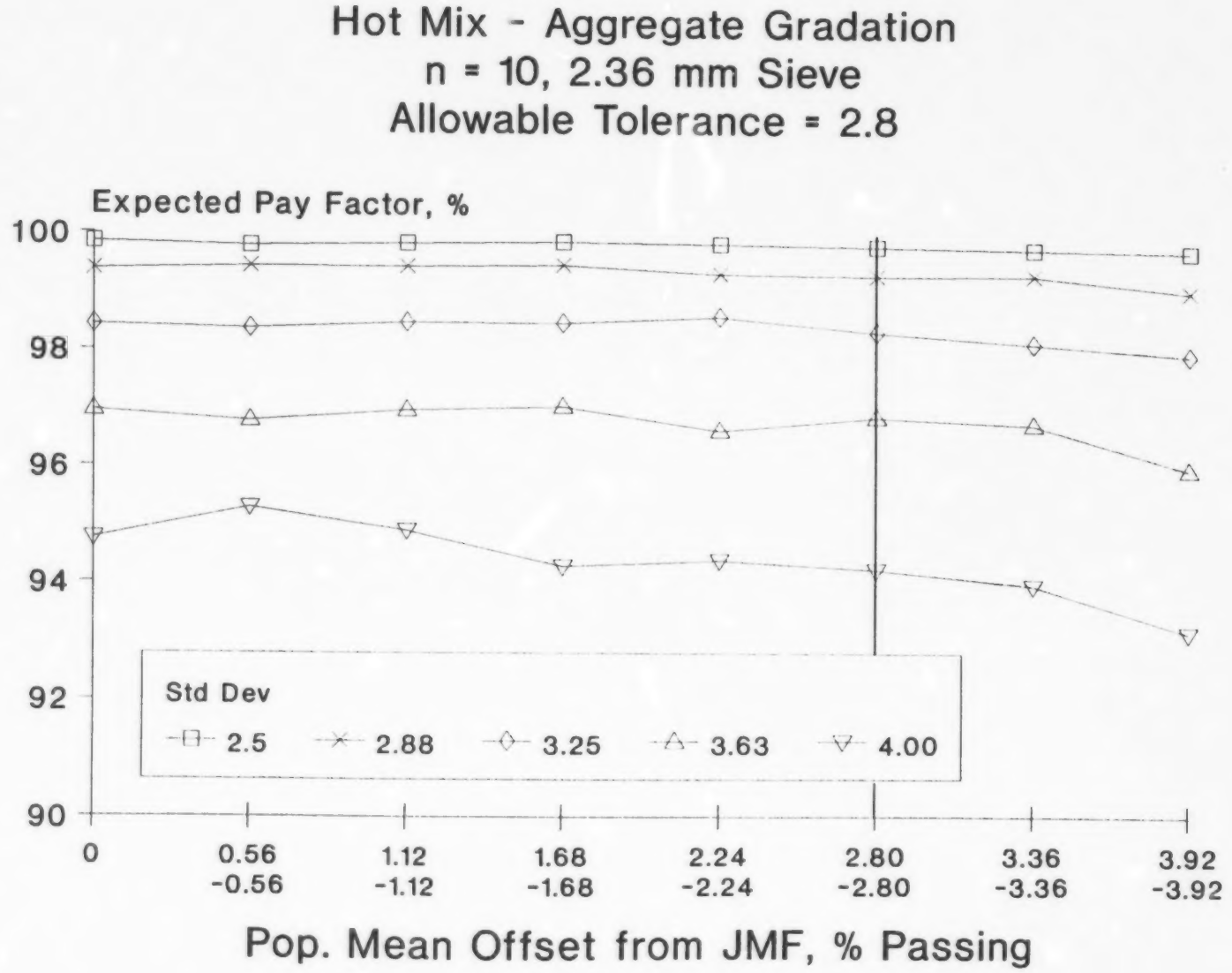


FIGURE 32. OPERATING CHARACTERISTICS FOR HOT MIX - GRADATION FOR 2.36 mm SIEVE, n = 10

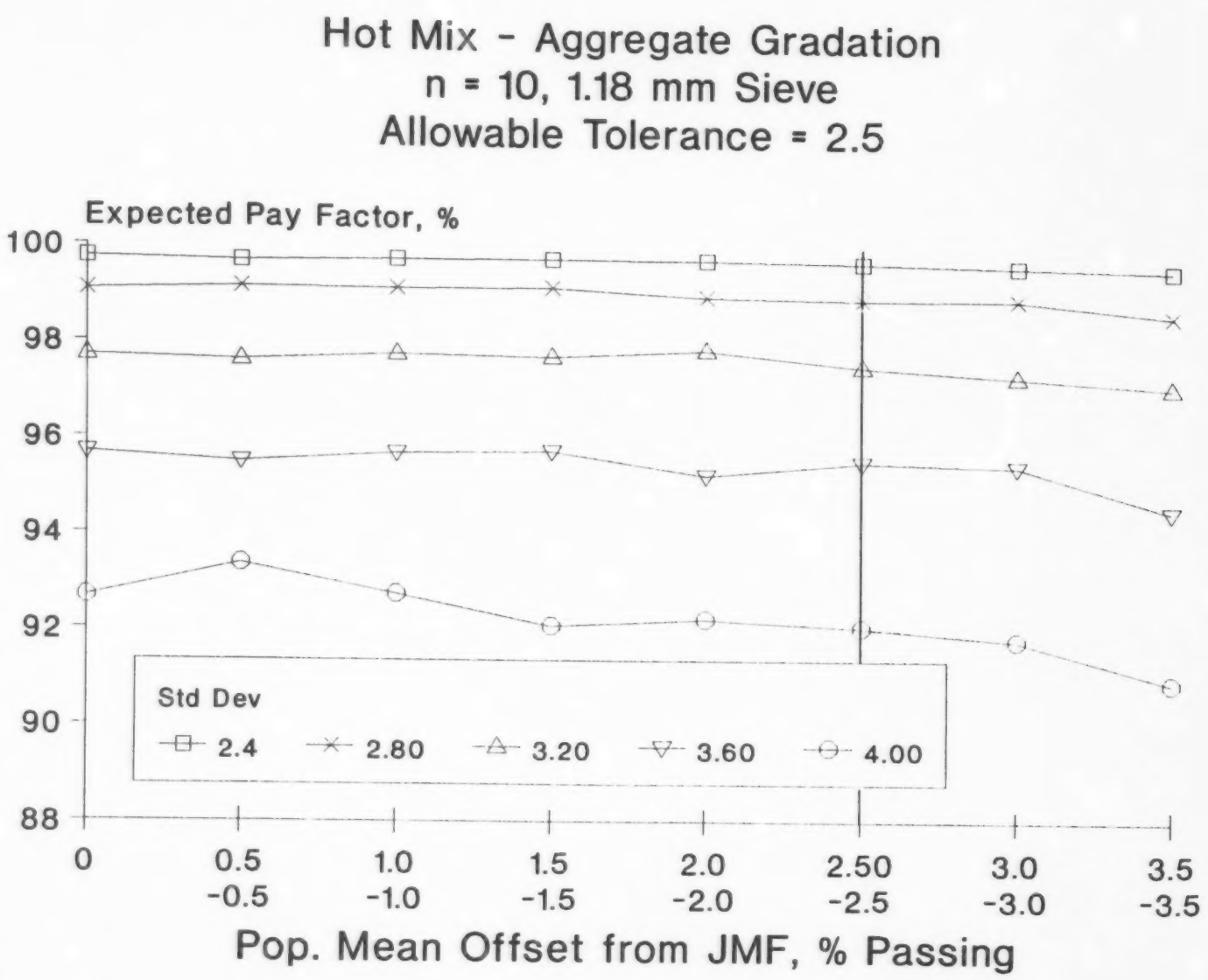


FIGURE 33. OPERATING CHARACTERISTICS FOR HOT MIX - GRADATION FOR 1.18 mm SIEVE, n = 10

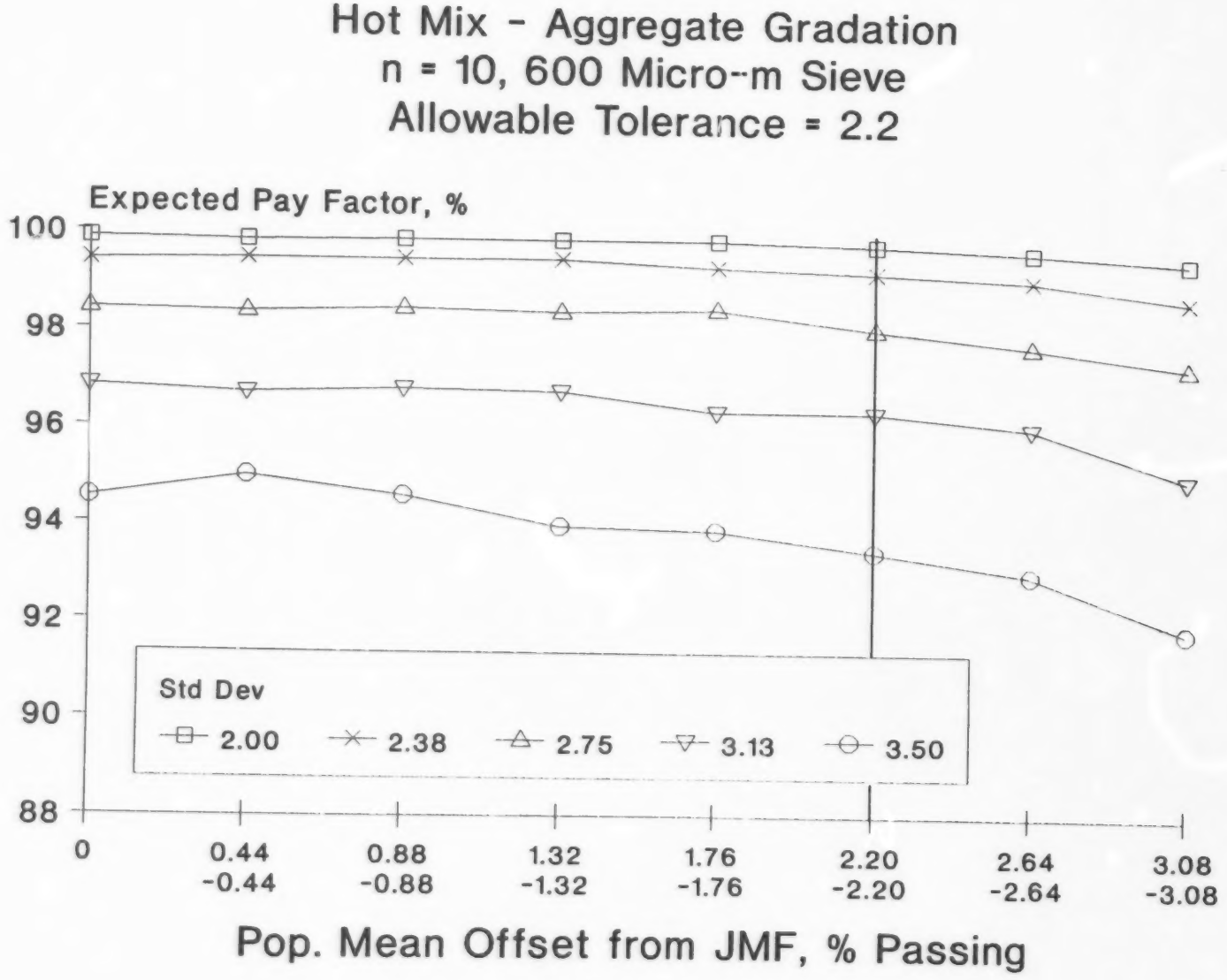


FIGURE 34. OPERATING CHARACTERISTICS FOR HOT MIX - GRADATION FOR 600 μm SIEVE, n = 10

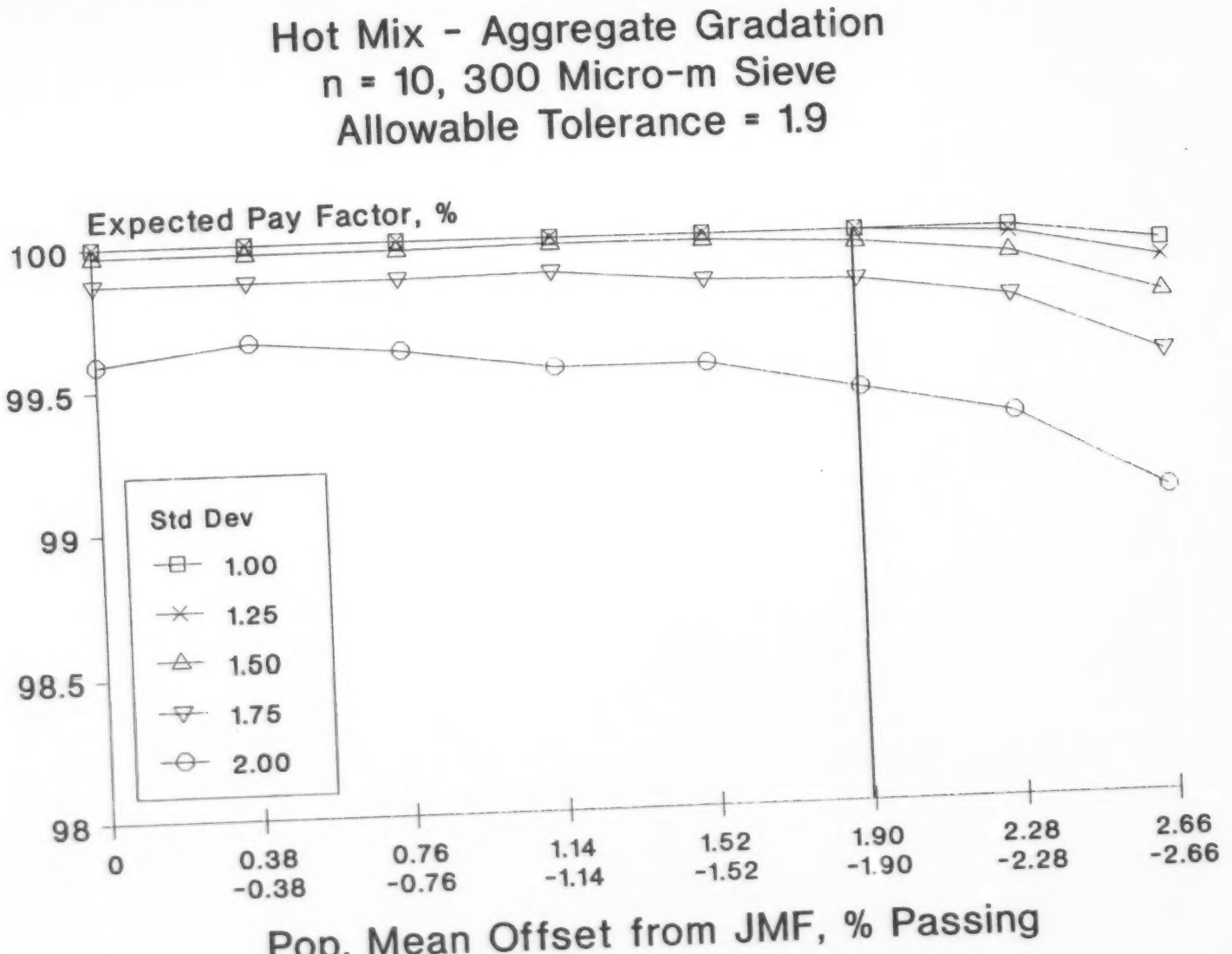


FIGURE 35. OPERATING CHARACTERISTICS FOR HOT MIX - GRADATION FOR 300 μm SIEVE, n = 10

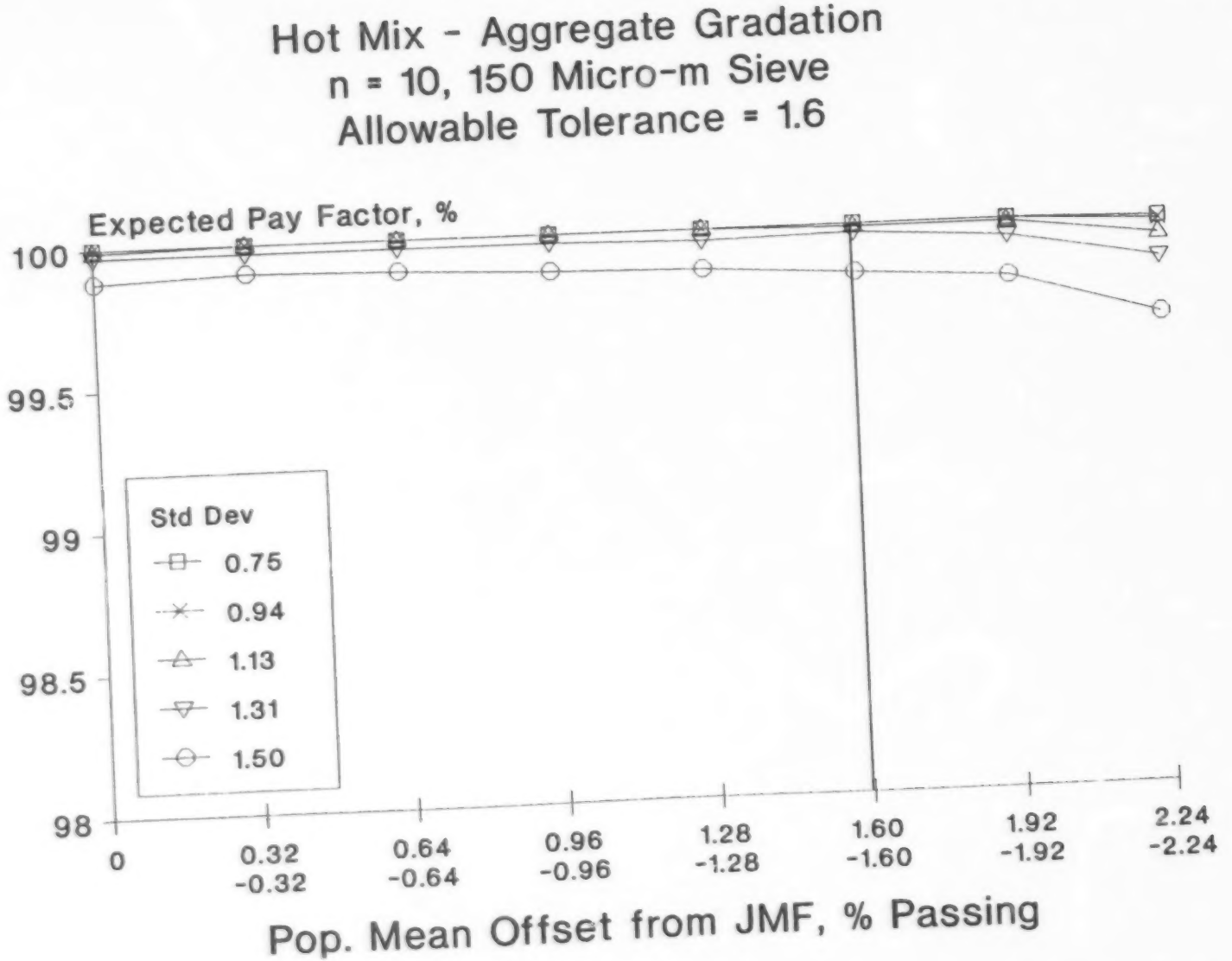


FIGURE 36. OPERATING CHARACTERISTICS FOR HOT MIX - GRADATION FOR 150 µm SIEVE, n = 10

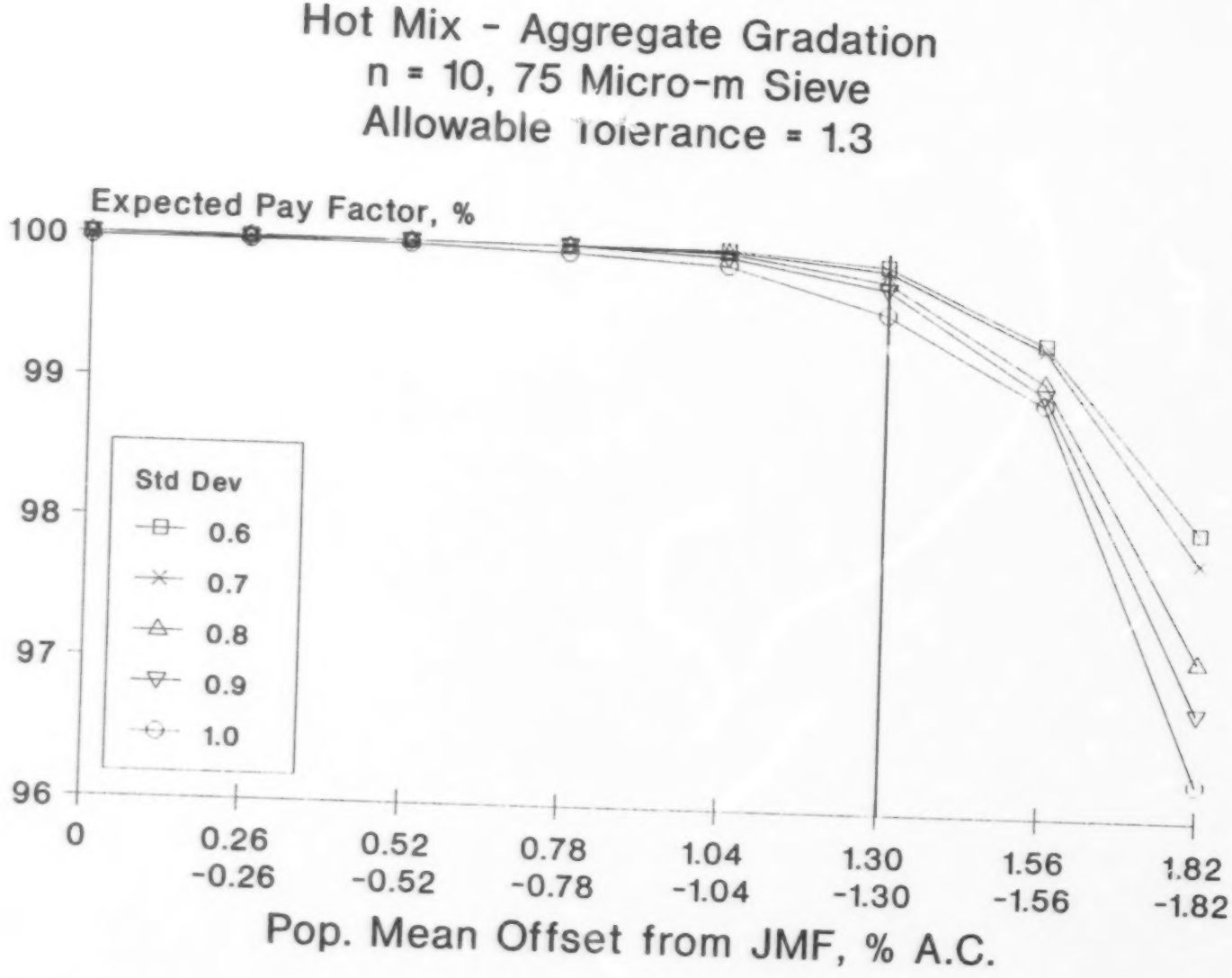


FIGURE 37. OPERATING CHARACTERISTICS FOR HOT MIX - GRADATION FOR 75 μm SIEVE, n = 10

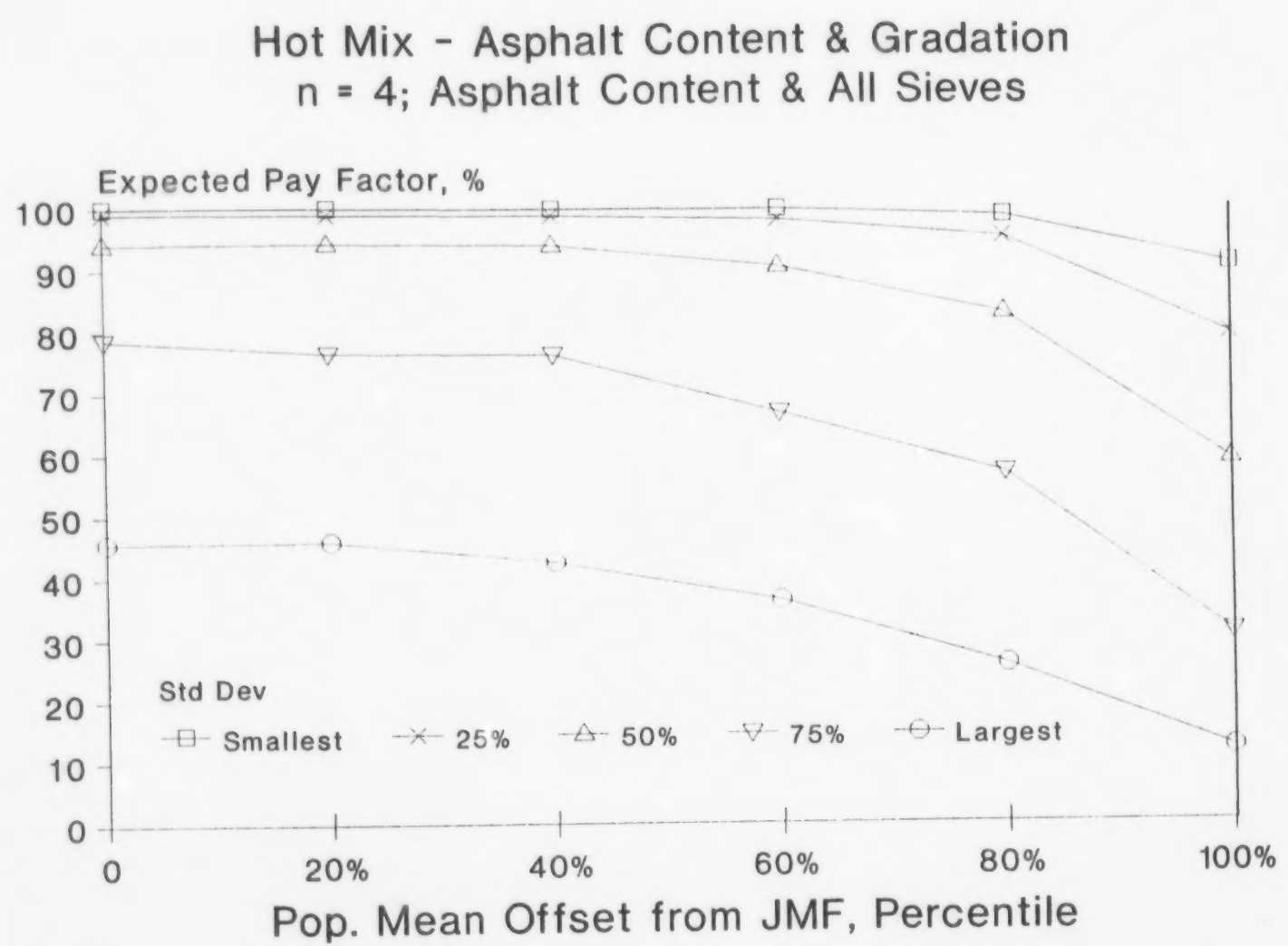
Since it incorporates both the sample mean and standard deviation (or Range) when calculating PWL, there would be no need to worry about limits for either mean or range.

Combined Effect of Asphalt Cement Content and All Sieves

As noted in the sections above, the acceptance procedures call for adding the adjustment points for asphalt cement and up to 11 sieves to obtain the final payment for the lot. At first glance, the OC curves in Figures 20 through 28 seem to indicate that the cumulative effect of considering all sieves in the payment determination should not be too severe. The expected payments for population means within the tolerance limits and for the smaller σ values simulated are nearly 100 percent for most of the individual cases.

The expected payments for population means centered on the JMF and having the largest σ value simulated for each individual case range from 96 percent to 100 percent, with most above 98 percent. If the expected payment reductions for these individual cases are added, they total about 13 percent. However, it must be remembered that it is the adjustment points that are summed for asphalt cement content and for each of the sieves to determine the payment for the lot. If the adjustment points associated with the expected payment values for each of the individual cases are summed, a payment adjustment much greater than 13 percent is obtained. In fact, the adjustment points associated with the individual payment adjustments total over 50 adjustment points!

To determine the effect of combining the adjustment points for 11 sieves and asphalt cement content, several simulations were conducted for sample sizes of four sublots per lot. There are an infinite possible number of combinations of population means and σ values that could be simulated for the combined case of all sieves and asphalt cement content. To allow some results to be plotted, the population means and standard deviations that were simulated for each individual case were also simulated for the combined case. The OC curves for this simulation analysis are presented in Figure 38



Percentile means % of tolerance range
measured from JMF toward limits

FIGURE 38. OPERATING CHARACTERISTICS FOR HOT MIX - ASPHALT CEMENT CONTENT AND GRADATION FOR ALL SIEVES, n = 4

Six population means were simulated for each individual sieve or asphalt cement content. The population means ranged from the JMF target value to the allowable tolerance limit in increments of 20 percent of the tolerance limit. Five different σ values were simulated for each individual case. The five σ values were the same as those used in the individual simulations presented in the OC curves in Figures 20 through 28. These σ values were different for each individual sieve or asphalt cement content, and are referenced in Figure 38 as the smallest value, the largest value, and three intermediate values (the smallest value plus either 25%, 50% or 75% of difference between the largest and smallest value).

Figure 38 therefore considers only several of the infinite number of possible combinations. The 'best' case is for that of the smallest σ values. In the case of the two smallest σ values, the expected payments are quite high for population means within the allowable tolerance limits. The 'worst' case is for the largest σ value. It is in this case that the cumulative effect of adding the adjustment points becomes evident. The expected payment, even when all of the individual population means are centered on the JMF target, is less than 50 percent. This low value is obtained in spite of the fact that none of the sieves or asphalt cement content had expected payments less than 96 percent when the same population means and σ values were simulated for the individual cases (see Figures 20 through 28).

While this 'worst' case is not likely to occur, and if it does occur, the pavement may not be acceptable, the Ministry may still wish to consider the possible effect on payment level of accumulating adjustment points for 11 sieves and asphalt cement content.

Discussion of the OC Curves

In general, the acceptance procedures appear to work as intended by the Ministry. There are high expected payments for population means near the job mix formula target values, and higher expected payments for populations with lower σ values. The expected payments decline as the allowable tolerances limits are

approached and exceeded. This should provide the intended incentive for the contractor to reduce variability and to strive to meet the job mix formula target values. However, as suggested previously, the use of the PWL method is recommended as an alternative to using separate acceptance and payment determination procedures for mean and Range.

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